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# PREFACE

This is the first number of Vol. 52 of the QUARTERLY TRANSACTIONS of the American Institute of Electrical Engineers. It embraces the Institute's annual Pacific Coast convention held at Vancouver, B. C., August 30 to September 2, 1932, and the Middle Eastern District (No. 2) meeting held at Baltimore, Md., October 10-14, 1932; includes all of the technical papers and related discussion presented at these meetings that were recommended for publication.

Also there are included the recommended technical papers and related discussions presented at the first three sessions (automatic stations, electric welding, and communication) of the Institute's annual winter convention held in New York, N. Y., January 23-27, 1933. The remainder of the recommended 1933 winter convention material is scheduled for inclusion in the June 1933 quarterly number of the TRANSACTIONS.

A complete table of contents may be found on the first page, and the customary alphabetical index of authors on the last page.

As an explanation of inevitable inconsistencies that may be noted in this and the next subsequent numbers, it is significant to note that a change has been made in the basic reference dictionary by which the editorial staff is guided in the preparation of copy for publication.

Beginning January 1, 1933 "Webster's International Dictionary" (G. & C. Merriam) was adopted as the editors' guide and arbiter for all published matter. Material composed for publication since January 1 follows the new guide but, for economical reasons, standing material will not be changed. Thus, the two styles may appear side by side until all standing material has been published.

# Segregation of Hydroelectric Power Costs

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Associate, A.I.E.E.

## INTRODUCTION

THE economic and physical conditions of the territory served by an electric utility as well as the conditions of the utility itself are continually changing, which makes it important to analyze the different cost items periodically in order to determine the trend of the changes in costs that are taking place. An increase in system load requires new generating plants, transmission lines, distribution lines and substations, the cost of which varies and in turn varies the cost of power. The cost of distributing power varies with changes in the character and location of the load. The overall cost of power will also change with a change in wages, cost of fuel or cost of supplies and materials. An analysis of system power costs is of importance to the various electric utility engineers, as well as to the management, if the information is in such form as to be readily usable for their particular problems.

The analysis of the power costs of a hydroelectric generating station is complicated by the fact that no two hydro stations are alike and by the fact that the method of using the station in conjunction with the rest of the system determines how costs may be segregated. The following discussion is divided into three parts. The first section is a brief outline of the method used in segregating system power costs and the development of the fundamental cost items. The principles upon which the cost of power is usually based are stated in order to show how any section or group of unit costs fit in and effect the entire system costs. The second section has to do with the segregation of the power costs of hydroelectric stations into their component parts. The methods of developing the components for different classes of hydro stations are outlined. The peculiarities of hydro power are given in the last section and the method of determining an average cost of power for a hydro unit or hydro system is outlined.

## I—Outline of System Power Cost Analysis

The analysis of system power costs consists: first, of dividing the system into its component parts and determining the yearly expenses of each part; and second, of prorating the different yearly expenses for each division between demand costs, energy costs, customer costs, and any other special costs that may be of interest. The main divisions which are applicable to the usual system are as follows: Production, transmission, distribution, customer costs, and general costs.

In addition to the above, any special costs that do not apply to the system in general should be kept separate. Street lighting costs where the utility maintains the lighting system, street railway costs where operation and maintenance is by the utility, and electric appliance sales costs are examples of costs that should be kept separate.

The annual production costs can be prorated between different generating plants. The transmission, distribution, and customer costs divisions can each be divided into geographic divisions. The general costs are prorated between production, transmission, and distribution. With the above divisions of costs, the cost of power at any particular point on the system can be obtained.

The segregation of annual costs between demand, energy, and customer costs is the basis for the so-called three-part rate structure which has been in existence for many years. While the usual rate structure does not include the customer costs as a special item, it is recognized as one of the costs of power and is included with the demand costs. The demand costs are those costs that are proportional to the power or kilowatts, but are independent of the amount of energy used. The energy costs are those costs that vary with the energy used and are proportional to kilowatt hours. Customer costs are costs chargeable to each customer that are independent of the amount of power or energy and which are approximately the same for each customer.

The segregation of production, transmission, and distribution into demand costs and energy costs requires a careful analysis of how the equipment is to be used and how the costs are incurred. On steam generating plants, the annual fixed costs are assumed to be demand costs and the variable costs are energy costs. Distribution and transmission annual costs are usually considered demand costs.

In ascertaining the cost of power on most systems, the utility can be considered a "going concern" with a built up load that is usually growing. It is advisable to keep at all times a certain percentage of reserve capacity both in kilowatts for peak demand and kilowatt hours. The amount of reserve capacity is a matter of judgment determined from experience and is different on every system.

## II—Analysis of Hydroelectric Power Costs

The hydroelectric power station annual costs are practically all fixed costs; that is, the costs are about the same whether the plant turns out 5 per cent of the available energy or the maximum amount. The operating and maintenance expenses are the same regardless of the load factor on the plant, for supervision of a plant is required whether the turbines are operating or not. A small change could be assumed due to the in-

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creased maintenance with greater use and the change in the number of men required for continuous operation as against part time operation. The large items of the annual expenses are interest, depreciation, taxes and insurance due to the large investment required, which are fixed regardless of whether the plant operates or not. On first thought this would lead to the conclusion that all hydro costs are in the nature of demand costs, which is only true for certain hydro stations.

The energy output of a hydro station is limited to some potential value determined by the stream flow of the river. It may not be possible to use the entire potential output due to the fact that the periods of high stream flow do not necessarily occur at such a time as they can be used on the system, or the installed generating capacity may limit the output to the machine rating. Most hydro stations have some pondage or storage which makes them more valuable to the system in that more potential energy in the stream becomes available to meet the system load.

The cost of constructing a given hydro project will vary with the amount of generating capacity that is to be installed. However, the amount of variation is usually small in comparison to the total cost of the project. As an example, assume a hydro project having a fixed stream flow for a period of 24 hours with pondage available to store the entire flow for 12 hours. Under these conditions the same total energy can be turned out in 12 hours as is possible in 24 hours if the generating capacity of the plant is at least double the capacity required for continuous 24-hour service. In order to increase the maximum kilowatts above that required for a 24-hour continuous duty the plant requires additional capacity in the turbines, generators, transformers, oil circuit breakers, electrical buses, penstocks, water conduits, power house and surge tanks. The cost of the dam, reservoir, water rights, and lands are approximately fixed and in most cases represent the bulk of the cost of the project. It follows then that as the plant factor goes down, the cost per kilowatt of the project also goes down and the total annual costs are increased only the amount necessary for the added depreciation, taxes, insurance and interest.

The original cost of a project can be divided into three classifications; first, those costs which are approximately proportional to the generating capacity; second, those costs which are independent of the generating capacity; and third, those costs which would apply to both groups. Individual plant items are segregated in the following list in accordance with the above classification.

| Proportional to generating capacity | Independent of generating capacity | Proportional and independent |
|---|---|---|
| Turbines | Dam | Water conduits |
| Generators | Reservoir | Surge tank |
| Penstocks | Water rights | Power house |
| Transformers | Lands | Electrical buses |
| | Construction plant | Switching equip. |
| | Station service equip. | |
| | Control equipment | |

It is necessary to divide the third group between the first two groups in accordance with the estimated expenditures that would apply to each group, which leaves the two groups of proportional and independent costs. For the purpose of this discussion the annual costs that do not vary with the changes in kilowatt plant rating are called "base" costs, and the costs which are approximately proportional to the kilowatts are called "proportional" costs. The distinction between proportional first costs and proportional annual costs must be kept in mind. The first costs, which can be divided between proportional and base first costs do not vary directly with the proportional and base yearly costs as the yearly expense of operation and maintenance is considered as part of the base yearly costs. The balance of the base yearly costs are made up of the interest, depreciation, insurance, and taxes on the investment required for the base first costs.

Hydroelectric power stations are designed to exercise a particular function in carrying the system load which is determined by the stream flow characteristics, useful storage at the hydro site, and the type of system load. Hydro stations can be divided into the following four general classes, and for illustration an example of each class is given.

1. Complete development with complete storage; stations designed to utilize the entire stream flow energy during years of mean or minimum stream flow by means of storage. Chelan and Cushman.
2. Complete development with partial storage; stations that have storage or pondage available for taking care of the daily load variations but not enough to store all of the seasonal variation of stream flow for use when needed during the dry period of the year. Baker River and Long Lake.
3. Partial development; stations that are capable of carrying full load at machine rating continuously. Nisqually and Niagara Falls.
4. Complete development without storage or pondage; stations utilizing as much of the stream flow as is economically possible without storage or pondage with the help of auxiliary power. Rock Island.

By complete development is meant utilizing as much of the potential energy of the stream as is possible with the economical storage and type of load that is available. Each of the above classes is discussed separately.

## COMPLETE HYDRO DEVELOPMENT WITH COMPLETE STORAGE

The first type of project to be discussed is that of plants designed to utilize the entire potential energy of the stream during years of mean or minimum stream flow at any required load factor without wasting water by means of storage. Whether to use, in the analysis, the mean stream flow or the minimum or some stream flow in between is determined by the amount of steam standby on the system that can be used exclusively by that plant in case of water shortage. In the case of storage adequate to meet a number of low water years, the maximum stream flow which would be continuously available as determined by the mass diagram or stream flow hydrographs, is used, augmented by the steam standby. In any case the annual cost of the steam standby must be charged against the hydro project.

As an illustration of this type of development, Fig. 1 shows the yearly operation of a hydro power station by monthly averages. The necessary reserve capacity is not included in the following discussion of this assumed project. The yearly output of 35,000 average kilowatts is assumed to be backed up by enough standby energy to supply the difference between the low water stream flow years and the average energy available as determined by the stream flow records. There is assumed to be sufficient storage in the basin above the dam to store the excess energy that occurs during the months of March, April, May, October, and November to be used during the balance of the year, so that all of the energy in the stream is available to meet the load as determined by the monthly load curve. The amount of generating capacity necessary to meet the yearly peak is determined by the load which has both a seasonal variation in energy requirements and an hourly variation in daily load, the combination of the two determining the yearly load factor. In the illustration in Fig. 1, the monthly load factor is assumed to be 60 per cent for every month so that with the monthly variation in load as shown the yearly load factor would be 47.7 per cent. It is the hourly variation in load throughout the day and not the seasonal variation that has the large effect in determining the yearly load factor on the usual system. The variation of installed generating capacity with load factor is expressed by

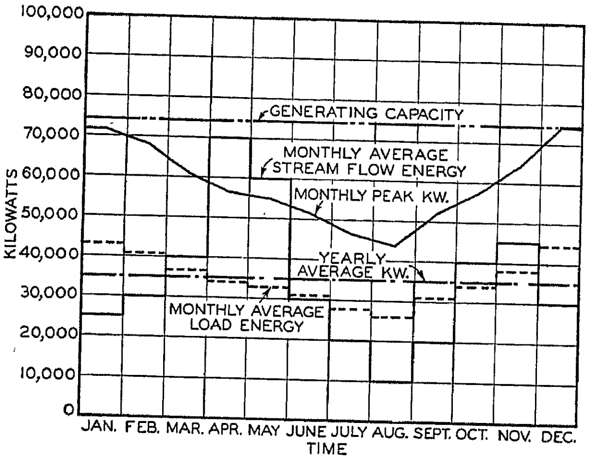

FIG. 1—YEARLY OPERATION BY MONTHLY AVERAGES OF A COMPLETE HYDRO DEVELOPMENT HAVING COMPLETE STORAGE

$$L = \frac{H}{K}$$

The following notation is used throughout the discussion.

$A$ = fraction of total annual costs of plant as built that would be necessary to run plant had it been designed for 100 per cent load factor.
$C$ = energy cost per kilowatt hour.
$C'$ = base cost per kilowatt hour.
$D$ = annual demand costs.
$D'$ = annual proportional costs.
$E$ = annual energy costs.
$E'$ = annual base costs.
$F$ = annual demand cost per kilowatt.
$F'$ = annual proportional cost per kilowatt.
$H$ = average kilowatts = kilowatt hours/8,760.
$K$ = peak kilowatts or kilowatt generating capacity.
$L$ = yearly load factor.
$M$ = total cost per kilowatt hour.
$P$ = plant factor.
$T$ = total annual costs.

On this type of development, the energy available in the stream ($H$) is constant so that the required generating capacity is inversely proportional to the load factor. This relation is shown in Fig. 2 for the hydro station in the above illustration. The energy is constant at 35,000 average kilowatts regardless of the load factor, while the required generating capacity for a load factor of 47.7 per cent is 74,000 kilowatts. If the load for the station had a load factor of 100 per cent it would be necessary to have installed only 35,000 kilowatts.

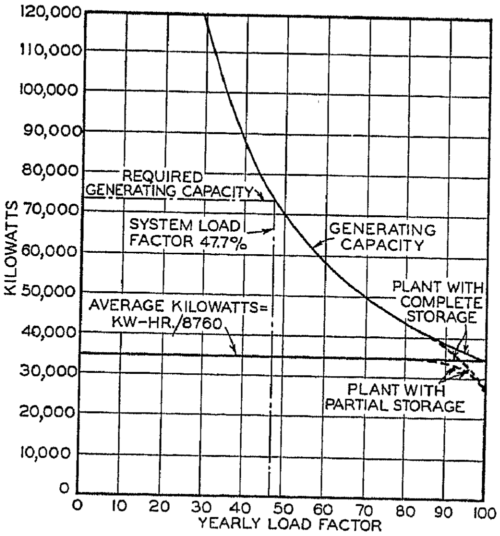

FIG. 2—VARIATION OF ENERGY OUTPUT AND GENERATING CAPACITY WITH LOAD FACTOR FOR COMPLETE HYDRO DEVELOPMENTS HAVING STORAGE

The relation between generating capacity and annual station costs is shown in Fig. 3. The total annual costs ($T$) is made up of the base costs ($E'$), and the proportional costs ($D'$). The base costs ($E'$) are constant regardless of the generating capacity while the proportional costs ($D'$) vary directly with the generating capacity. As the energy output is constant and as the generating capacity varies inversely with the load factor, the total cost per kilowatt hour can be expressed by

$$M = \frac{E'}{H\,8760} + \frac{D'}{KL\;8760}$$

$$M = C' + \frac{F'}{L\,8760}$$

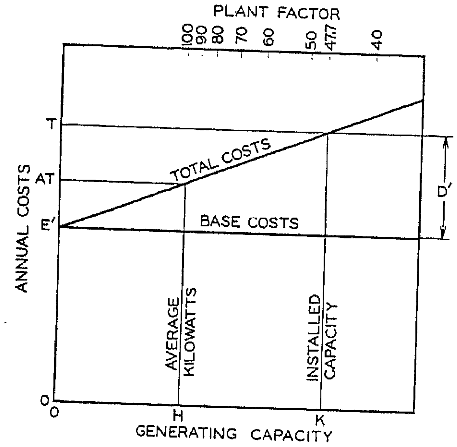

Fig. 3—Variation of the Annual Costs of a Hydro Station with Generating Capacity

$T$ = total annual costs as constructed
$D'$ = annual proportional costs as constructed
$E'$ = annual base costs
$A$ = fraction of total annual costs as constructed necessary to run plant designed for 100 per cent load factor
$K$ = peak kilowatt capacity
$H$ = average kilowatts = kw-hr. output/8,760

There are two methods of segregating the base and proportional annual costs on an actual project of this type. The first method would be to divide the actual construction cost between base and proportional and from these determine the base and proportional annual costs. The second method would be to obtain the slope of the total annual cost line shown in Fig. 3. which is the annual proportional cost per kilowatt ($F'$), by means of an estimate of what the annual cost of operating the plant would have been had it been designed for a 100 per cent load factor. Referring to Fig. 3 the slope of the total annual cost line is

$$F' = \frac{(T - AT)}{(K - H)} = \frac{T\,(1 - A)}{(1 - P)K}$$

The base cost per kilowatt hour is

$$C' = \frac{T\,(A - P)}{\mathrm{H}\;8760\;(1 - P)}$$

It is evident from the above that the proportional cost per kilowatt ($F'$) is the demand cost of service and that the base cost per kilowatt hour ($C'$) is the energy cost of service. Likewise the annual proportional costs ($D'$) are annual demand costs and the annual base costs ($E'$) are annual energy costs.

Fig. 4 shows the cost per kilowatt hour for different load factors as calculated for the power station referred to in Fig. 1. The base or energy cost of service is constant while the proportional or demand cost of service varies inversely with the load factor.

## Complete Development with Partial Storage

A large proportion of the hydroelectric developments does not have adequate storage to meet the system load without wasting water during the mean or minimum stream flow year and so would come in the classification of partial storage. For the purpose of this discussion all plants that have pondage enough to take care of the maximum daily peak from daily stream flow but not enough for complete storage are considered partial storage plants.

In the example of this type of development, as shown in Fig. 5, storage adequate to meet the variation in the daily load curve as well as to raise the station output a small amount during the low water months of the summer, is assumed. The same load curve is assumed as was shown for the complete storage development in Fig. 1. The yearly average potential stream flow energy is 50,000 average kilowatts and the difference between the usable and the potential is 15,000 average kilowatts which is wasted.

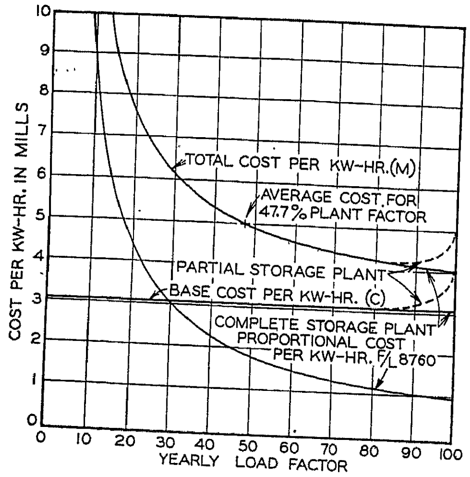

Fig. 4—Power Cost Curves for Complete Hydro Developments Having Storage

Due to the restricted storage the generating capacity for the plant if designed for 100 per cent load factor would be 27,000 kilowatts instead of 35,000 kilowatts and the energy output would also be cut down. As the generating capacity of the plant is increased from 27,000 kilowatts to 44,000 kilowatts the usable energy output is also increased from 27,000 to 35,000 average kilowatts, and the yearly load factor reaches approximately 80 per cent which is due to the variation in seasonal load and not the variation in the daily load curve. It is necessary to install additional generating capacity to take care of the hourly load variation which does not increase the energy output. It is evident that to increase the energy output above 35,000 average kilowatts without the use of auxiliary power, it would be necessary to increase the load during the period of the year when there is an excess of stream flow, which would be in the nature of secondary power. The variation of energy output and generating capacity is as shown in Fig. 2, and is the same for this assumed development as for the one shown in Fig. 1 for load factors from zero to 80 per cent. Between 80 and 100 per cent load factors the energy available and the generating capacity are less, due to the restriction imposed by the type of site.

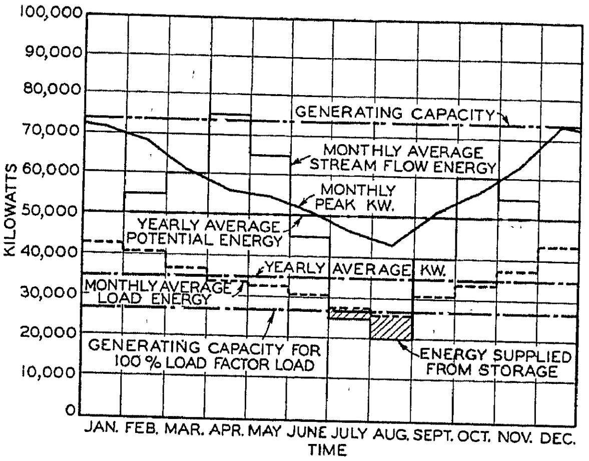

Fig. 5—Yearly Operation by Monthly Averages of a Complete Hydro Development Having Partial Storage

The same power cost equations with correction factors would apply to this type of development as for the development with complete storage. The proportional cost per kilowatt in the case of partial storage developments may be obtained by the second method as outlined for complete storage developments. In this case an estimate of annual expenses is made for operating the plant with generating capacity corresponding to the annual average load as if it were 100 per cent load factor, and the correction factors applied to take care of the decrease in kilowatt hours.

The cost per kilowatt hour curves for the partial storage plant, Fig. 4, are the same as for the complete storage plant as long as the energy output is the same. The base cost per kilowatt hour above 80 per cent load factor is increased by the ratio of the average yearly load divided by the average usable energy, at any given load factor. This in turn increases the total cost per kilowatt hour at those load factors.

## Partial Development

Under most circumstances the hydro plant is designed to utilize as much as is economically possible of the available energy of the stream and so there are very few finished projects that would come within the partial development classification. The Niagara Falls Power stations are outstanding examples of this type of development as the amount of water that can be taken from the river is fixed by treaty between Canada and the United States. The stream flow that is allotted for power purposes is a certain percentage of the minimum flow of the Niagara River. Uncompleted plants that have been designed for complete development of the river later would sometimes come under this classification if the installed capacity is less than the usable potential average kilowatts throughout the period of the investigation of power costs. The characteristic of this type of development is that the plant is capable of furnishing load equal to the installed capacity at 100 per cent load factor.

Fig. 6 shows conditions of stream flow and load for a development of this class. The same load and generating capacity as assumed in the two classes of development, previously discussed, are shown.

There are two ways of looking at this type of project which depends upon the limiting factors that caused the stream to be partially developed. One is that the amount of water that can be taken from the stream is fixed and the other is that the installed generating capacity is fixed. If the amount of water that can be taken from the stream is fixed, the plant output is fixed, and the cost analysis would be the same as for a plant having complete storage. Some plants designed many years ago with a minimum of generating capacity could not have additional generating units added now without rebuilding the entire plant, and until that is done they can be called fixed capacity plants.

With a fixed generating capacity plant, the kilowatt hour output is proportional to the load factor as shown in Fig. 7. The yearly cost of operating the project is fixed so that the cost per kilowatt hour is inversely proportional to the load factor and the following equation would hold. The cost per kilowatt hour is

$$M = \frac{T}{KL\,8760}$$

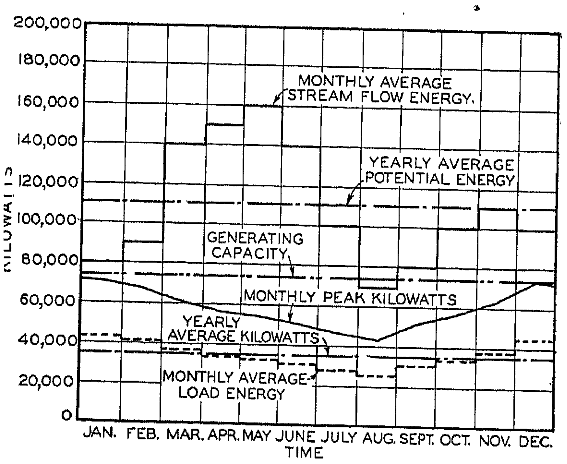

Fig. 6—Yearly Operation by Monthly Averages of a Partial Hydro Development

The cost per kilowatt ($T/K$) is the demand cost of service, so that for this type of project all of the station costs are considered demand costs.

## COMPLETE DEVELOPMENT WITHOUT STORAGE OR PONDAGE

A hydro project without storage or pondage cannot usually be used economically without other means of supplying the system load demands during periods of low stream flow. The stream flow fluctuations never follow the load demand of a system supplying the usual type of loads without some pondage so that this type of site could not be developed and used to the best advantage without other means of supplying power.

If the stream is flashy, the plant cannot be relied upon to furnish the power when required, so that its development would be used to supply energy only. As long as the energy can be used on the system the cost per kilowatt-hour would be the same regardless of the load factor and can be expressed by

$$M = \frac{T}{\text{Kw-hr.}} = \frac{T}{H\,8760}$$

and in this case all station costs are energy costs of service. The demand cost of service is determined from the cost of the necessary auxiliary power.

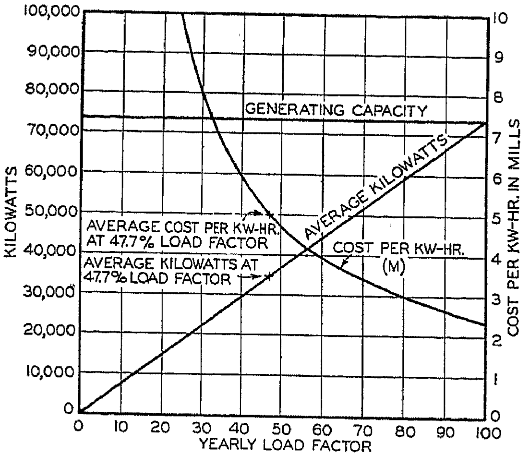

FIG. 7—VARIATION OF ENERGY OUTPUT AND POWER COST FOR A HYDRO DEVELOPMENT HAVING A FIXED GENERATING CAPACITY

The value of the average kilowatts (*H*) is determined from the duration curve of the stream. Fig. 8 shows a duration curve for this type of development. The average kilowatts or kilowatt-hours available in the stream with different installed generating capacities is also shown in Fig. 8 and is calculated from the duration curve.

The annual costs per kilowatt-hour for the development with different values of installed capacities are shown in Fig. 9. The most economical development would be 60,000 kilowatts providing the night load on the system is great enough to use the entire power from this station. It should be noted that if it were necessary to provide additional demand capacity by steam or more units in other stations in order to use the energy from this type of station, the cost of the additional demand capacity would have to be included with these station costs in determining the economical development.

The above discussion of the four main types of hydroelectric plants could not be construed as a complete discussion, as some stations are constructed for a particular type of load that will only fit in with other plants on the system. A plant may be designed for use during only a portion of the year and other plants may be designed to furnish energy during part of the year and demand capacity during other times of the year. Other plants may be on the dividing line between any two of the above discussed types. Such plants would require special analysis as to the use for which they are intended in accordance with the principles as outlined above.

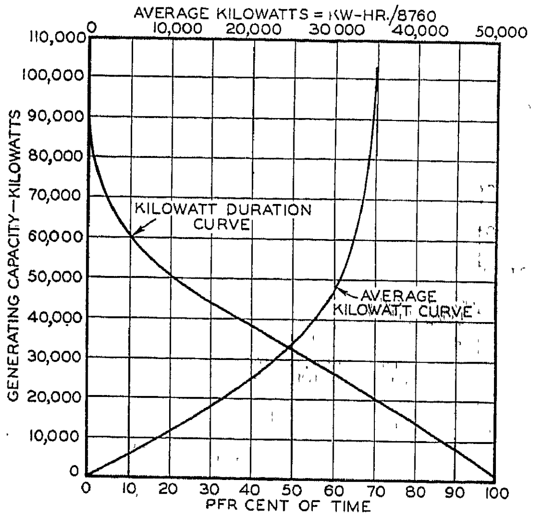

FIG. 8—DURATION AND ENERGY CURVES FOR A HYDRO PLANT HAVING NO STORAGE OR PONDAGE

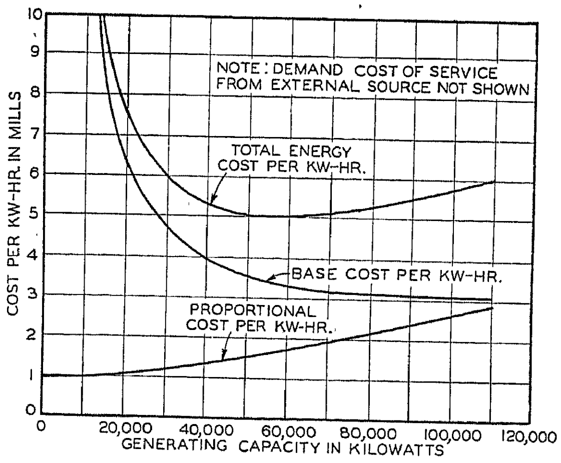

FIG. 9—ENERGY COST OF POWER FOR A HYDRO PLANT HAVING NO STORAGE OR PONDAGE

In the case of transmission lines from the hydro station to the system transmission network, their annual cost should be included with the hydro station annual costs, and they can be analyzed similarly to the station costs.

## III—Average Cost of Hydro Power

The discussion so far has to do with the segregation of hydroelectric power cost into the two components of demand and energy costs for plants delivering energy up to their capacity. This condition is not realized often in practise but the relation between the demand and energy costs, as determined above, is fixed within limits regardless of the loading on the plant.

The usual hydro system that has a growing load can not construct new hydro plants in such a way as to have the system annual expenses increase proportionately as the load increases. As a new plant is added, which requires at the beginning a large outlay for base costs, the yearly expenses increase by a large percentage while the yearly growth in load may be only normal or may be less. Before the plant is loaded up there is likely to be a period of many years in which the annual expenses are practically constant, but as the load increases the cost of power decreases. The length of time to be used in arriving at the average cost of power is determind by the use for which the investigation is made. The annual cost each year is important for operating, while for rate analysis an average cost over a period of years is essential. The immediate past experience of the utility and the future expected conditions as to load growth and the expansion program are essential in determining the average power cost over a period of years, to be used for rate investigation. The number of years to be used in determining this average cost is important as it effects the cost materially. Past experience should be included back as far as a point in the life of the system when the accumulated revenue is equal to the accumulated expenses. How far into the future the period of investigation should extend is determined by the length of time the forecasts of construction program and load growth can be made and still be within the desired accuracy of the investigation.

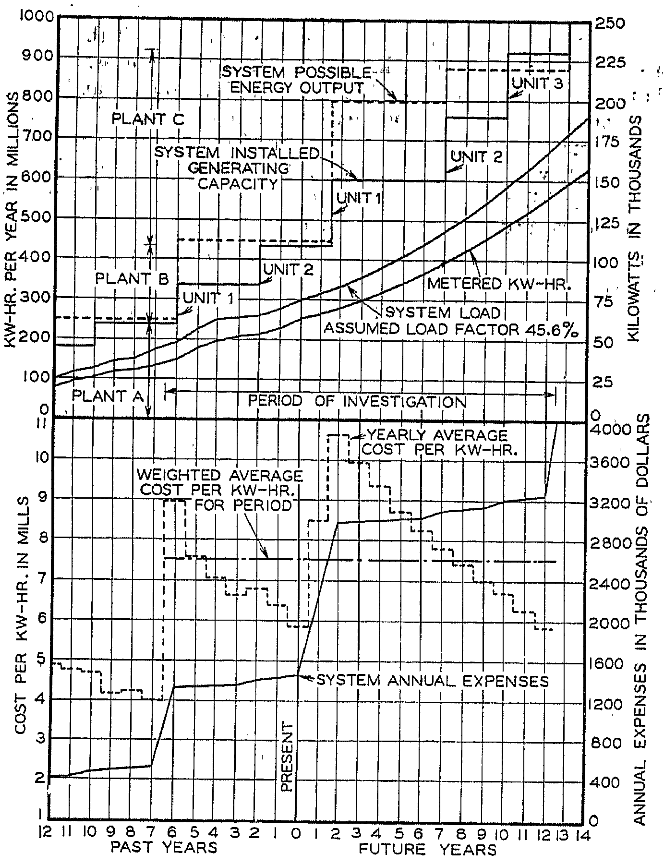

FIG. 10—LOAD, CAPACITY, EXPENSES AND POWER COST FOR A HYDROELECTRIC SYSTEM OVER A PERIOD OF YEARS

As an illustration of the relation between construction program, load growth and average cost of power, the yearly statistics of an assumed system are shown on Fig. 10. The upper diagram shows the growth in load that has occurred in the last twelve years and the expected growth during the next fourteen years. The rate of growth has been approximately 7 per cent in the past and is expected to continue at the same rate in the future. The present load is being carried by the two hydro stations, A and B. The proposed hydro development plant C is expected to take care of the system growth for the next 13 years and the proposed construction program is as shown on the upper diagram.

The system annual expenses are shown on the lower diagram. It is assumed that the accumulated expenses were equal to the accumulated revenue at the time plant B was constructed 6 years ago. The average cost of power for the period of investigation, which extends into the future through the known construction program is weighted to take into consideration the varying yearly average cost per kilowatt hour and increase in load.

It is evident that if the revenue is based on the average cost of power over the period of investigation, that the yearly revenue is insufficient at times to meet the yearly expenses. The utility would have to borrow money to take care of this condition, so that interest would have to be charged under certain conditions for the use of the borrowed money.

By such an analysis of the past and future conditions of the utility some point in the period of investigation can be found that will have a system load and system expenses that will give an average cost of power for the period.

### SUMMARY

In an analysis of electric power costs there are two elements that make up the load; first, the power or kilowatts, and second, the energy or kilowatt hours. It is, of course, impossible to have one without the other and the relation between the two is expressed by the load factor. In the analysis, either the power is assumed to be constant and the energy will vary with the load factor or the energy is assumed to be constant and the power or kilowatts will vary with the load factor. In the analysis of hydroelectric power costs, the energy output of the generating station per year is fixed by the stream flow so that the kilowatts are assumed to vary inversely with the load factor.

The units of cost, in the above analysis of hydroelectric power costs, are so arranged that if the system load factor changed from what it had been when the plant was designed, the annual cost would change to correspond to that of a plant designed and built for the new load factor. If the revenue from all the different loads supplied by the plant is based on the demand and energy costs as derived for the plant, the total revenue received will correspond to the annual expenses of the station as if designed for the plant load factor. Diversity losses, reserve capacity and customer costs must of course be considered in arriving at the annual costs and plant load. The average cost of power over a period of time by the above method is the same as would be found by the method where all station costs are considered demand costs, but the cost per kilowatt hour at load factors above the system load factor is greater than by the demand cost method, but less at load factors below.

One of the principal uses of the analysis is in the economic selection of the method, and the location of generating power, to meet the system load growth, when there are several hydro sites to compare. The analysis is also useful in determining the economic combination of steam and hydro power.

## Discussion

**J. S. Moulton:** There are two principal purposes for which analysis of power costs is required:

1. The comparison of relative costs of various plants or combination of plants which may be selected in constructing or enlarging a power system for the purpose of obtaining the lowest total annual cost.
2. The analysis and apportionment of costs among various classes of load so as to compare the allocated cost of service with the revenue secured from these various classes.

The problem of construction program, the elements which must be considered, and the manner of attack, has been very well covered by a number of authors in the past. Papers by Mr. A. H. Markwart appearing in the *Journal of the Franklin Institute*, August 1927, pages 176-190, and *Electrical West*, September 1930, page 136, are particularly valuable contributions to this subject. In the development of the most economical construction program, it is not necessary to segregate the costs of various projects under consideration into so-called demand and energy components. It is usual to develop costs for a number of different installed capacities and to determine for each of these capacities the cost per kilowatt hour for various load factors. By means of methods described in the above mentioned papers, the most economical combination of steam and hydro may be determined for various load factors. From these data and from known system characteristics, a construction program may be laid out. For any particular system, there are of course many related factors such as partial investments in potential developments, requirements for local supply at some particularly weak point on a transmission network, and many others which must be given consideration.

The division of total generating plant costs between demand costs and energy costs is required for a cost of service analysis. Mr. McCrea's paper, after some discussion of costs, reaches the conclusions that the base cost per kilowatt hour, assuming that a plant could be constructed to operate at 100 per cent load factor, is the energy cost of service, and that the additional cost incurred by reason of less than 100 per cent load factor operation is the demand cost of service. The first of these conclusions is in reality a premise upon which the validity of much of the balance of the paper depends. It is perfectly correct to assume in case of 100 per cent load factor operation that the costs involved can be expressed on a kilowatt hour basis. It is equally correct, however, to assume that they can be expressed on a per kilowatt basis and this is the basis on which power is sometimes sold to high load factor consumers, particularly in the vicinity of Niagara Falls. The desirability of considering base costs as demand costs of service rather than an energy cost of service is illustrated by Fig. 7 of the paper. In this figure it is shown that with a fixed generating capacity installed, if the average kilowatts falls below 100 per cent load factor, the cost per kilowatt hour increases. If such minor items as possible variation in operating expense and maintenance of a hydro plant with change in output are neglected, the cost per kilowatt of capacity remains the same. From a rate making standpoint, if the output of such a plant is sold on a kilowatt hour basis on the assumption that the plant will operate at 100 per cent load factor, and conditions change so that it operates at less than this load factor, it is obvious that at the fixed price per kilowatt hour the total plant costs will not be met. If, on the other hand, the capacity is sold on a kilowatt basis, then the total plant costs will continue to be met regardless of how the load factor may vary.

If rates were fixed purely from a cost standpoint, they should be fixed so that the utility would be reimbursed for its costs, including a fair return on the value of its property, no matter how the system load factor might vary. It is probably aside from the proper discussion of this paper to discuss rate making. It should be pointed out, however, that most of the costs of a hydroelectric development are fixed when once made, and that if a part of these costs is assumed for purposes of an analysis to vary with the kilowatt hours produced when in reality they do not, a decrease in the system load factor from that assumed will result in a failure to meet the total project costs, while an increase in the system load factor will result in the production of more than the project costs. A utility can seek to guide the development of its loads by carefully considered rates, but changes in load factor are not entirely within its control. Rate making must consider many things in addition to an allocated cost of service, and in most instances schedules will include part of the demand cost and part of the consumer cost in the energy charge. This is not a reason, however, in a cost analysis, for assuming that fixed costs vary with kilowatt hour output.

**W. S. McCrea, Jr.:** The conclusion reached in the paper as to the cost of power for 100 per cent load factor operation is a little different than as stated in Mr. Moulton's discussion. True, the base cost per kilowatt hour is the energy cost of service, but in addition to the base cost per kilowatt hour, there is a proportional cost per kilowatt even at 100 per cent load factor, which would be the demand cost of service. This is shown in Fig. 4 of the paper. The energy cost of service at 100 per cent load factor is shown as over three mills per kilowatt hour and the demand cost of service is less than one mill per kilowatt hour. The total cost of service is the energy cost plus the demand cost of service and is four mills per kilowatt hour at 100 per cent load factor. The demand cost of service if expressed in units of cost per kilowatt would have the same value at any load factor.

If the load factor of a given load is known or could be assumed, it is perfectly correct to express the total cost as either cost per kilowatt or cost per kilowatt hour; or some combination of the two. The question which the paper attempted to answer is how much the total cost would be at different load factors. The method of solving the problem was to determine the variation of construction costs with generating capacity and from this the variation of the annual costs of the plant with the plant factor.

The units of cost in this analysis are so arranged that if the system load factor changed from what it had been when the plant was designed, the annual cost would change to correspond to that of a plant designed and built for the new load factor. In other words, the total cost of power at 100 per cent load factor is the same as if the plant were built to deliver all of its available energy at 100 per cent plant factor.

The fallacy of considering all hydro station annual costs in the nature of demand costs is due to the fact that the amount of energy available is limited by the stream flow, which, in the economically developed plant, is considerably less than if the energy output were limited by the generating capacity as is the case in a steam plant. The results obtained by the two methods for the cost of power at different load factors are very different. The total cost of service by either method is the same at the system load factor, but the cost at load factors above the system load factor is greater by the above analysis than by the demand cost method, but less at load factors below.

It is interesting to note the effect on the economical combination of steam and hydro power of the above method of analysis as against the demand cost method. If we assume the cost of steam and hydro to be the same at the system load factor, the cost of hydro power will usually be greater than steam at the high load factors by the above method of hydro cost analysis, and lower than steam at the low load factors. If the demand cost method were used the results would be just the opposite.

The economical combination of steam and hydro under the above conditions will result in the hydro station being designed with generating capacity enough to take the larger portion of the peak load and the steam station designed for the continuous or high load factor load. The combination of the two may result in an average cost of power lower than either hydro or steam alone.

# The Reading Company's Philadelphia Suburban Electrification

G. I. WRIGHT*
Member, A.I.E.E.

THE electrification of the Reading Suburban Service in the vicinity of Philadelphia was authorized October 25, 1928, and was placed in operation July 26, 1931. The lines now under electric operation include 65 route miles and 157 track miles which will be increased by January 1, 1933 to 87 route miles and 203 track miles. These lines, as shown on the map, (Fig. 1) consist of six branches and cover all the suburban territory north of Philadelphia between the Schuylkill and Delaware Rivers.

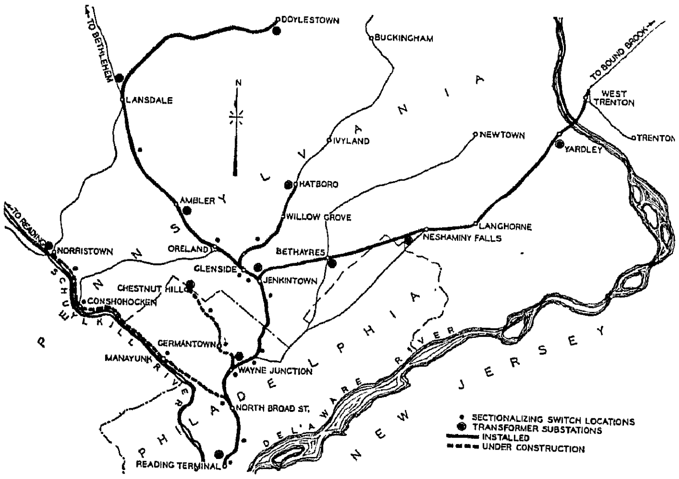

FIG. 1—MAP OF SUBURBAN ZONE

Steam operation in this territory has been in service for many years, the Reading being one of the oldest railroads in this country. In the last ten years, however, it has met severe competition from private automobiles, buses, a new subway, and the Pennsylvania Railroad electrified lines, and this has resulted in serious loss of traffic and revenue to the railroad.

The Reading Company was faced with two alternatives, either to continue steam operation, where the only means of cutting cost of operation was to reduce the number of trains, thus further impairing the service and resulting in additional losses of traffic, or to provide a modern superior electrified service, which in addition to other advantages, would materially reduce the operating cost per train mile. It was felt that this would justify the operation of more frequent trains, which with a 20 per cent increase in schedule speeds, greater cleanliness and more attractive equipment, would attract an increased traffic.

In the general design of the electrification and the choice of system and of transmission voltages, it was necessary to give careful consideration to future electrification plans for the system as a whole. It will be noted from a reference to the map of the Reading Company's system (Fig. 2) that the suburban electrification lies within a circle, with its center at Jenkintown, and a radius of 20 miles. It will also be noted that with the same center, a circle with a radius of 80 miles, takes in the Reading Company's lines to Reading and Pottsville; to Bethlehem, to Jersey City (C.R.R. of N.J.); also the Reading and Central Railroad of New Jersey lines in New Jersey, and the Jersey Central's main line from Jersey City to Mauch Chunk. Incidentally, this area also includes the main line of the Lehigh Valley and the D.L.&W. in the same territory; the Baltimore & Ohio, from the Susquehanna River to Philadelphia, the P.R.R. from the Susquehanna to New York and its main line from Lancaster to Philadelphia. There is probably a larger amount of railroad traffic in this area than in any similar area in the world.

It was desired to provide satisfactorily and economically for the suburban electrification in the smaller area and at the same time arrange the initial electrification so that it could be amplified and extended some time in the future to take care of the larger territory.

The single-phase 25-cycle system of electrification was adopted as fulfilling these requirements and at the same time had the advantage of being standard with the system used by the Pennsylvania Railroad in the electric operation of its Philadelphia Suburban service and its electrification from Washington to New York, now under construction.

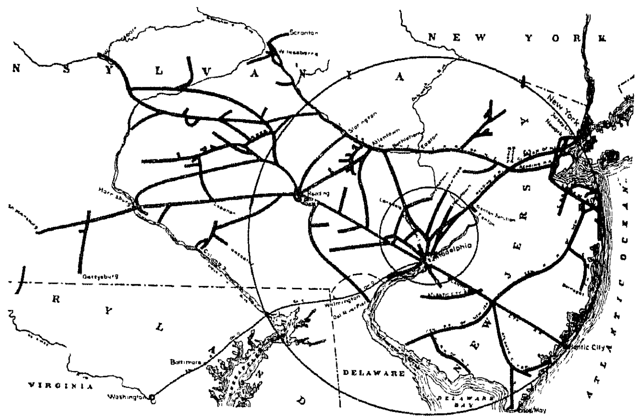

FIG. 2—MAP OF READING SYSTEM

## POWER SUPPLY AND SUBSTATIONS

It was decided to purchase power and the Philadelphia Electric Company installed a frequency changer station at Wayne Junction adjacent to the Reading Company's main substation. A 3-wire distribution system having 12,000 volts between trolley and rail, 24,000 volts between feeder and rail and 36,000 volts between feeder and trolley wire was adopted to transmit the power to the railroad's nine autotransformer substations whose locations are shown on the map. These substations are all designed on a unit basis and consist of one, two or three 2,000-kw. autotransformers and are designed so that as loads increase in the future, these transformers can be moved to outlying points and replaced with 4,000-kw. transformers without any other change to the substations.

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*Chief Elec. Engr., Reading Co., Philadelphia, Pa.

*Presented at the Pacific Coast Convention of the A.I.E.E., Vancouver, B. C., August 30-September 2, 1932.*

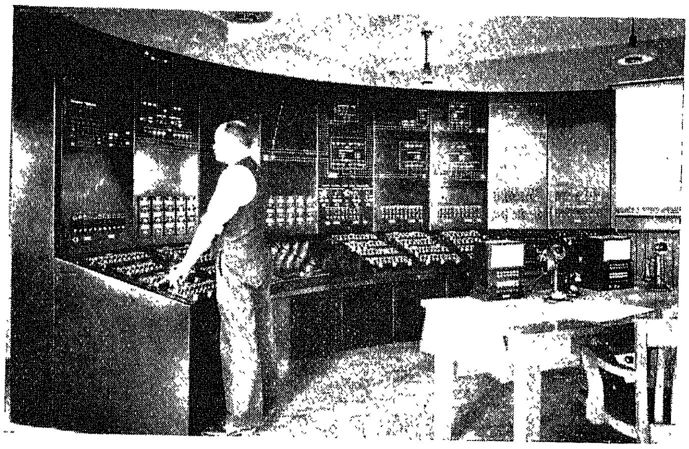

Fig. 3—Supervisory Control Desk—Power Dispatcher's Office

Provision is made for the addition of duplicate single-phase, 66-kv. transmission lines to parallel this 3-wire system. Electrification beyond the initial territory can be carried out by using either a 2- or a 3-wire distribution system fed from one or more outlying points through suitable step-down transformers. This arrangement permits tapping the 66-kv. lines at any desired intermediate points to augment the 3-wire system through so-called "three-winding" transformers.

All substations and switching stations are non-attended and are operated by supervisory control. Details of the power contract, power supply system, substations, and supervisory control, are described in the articles listed in the bibliography and in the interests of brevity, will, therefore be omitted from this paper.

## Catenary Structures and Foundations

*General.* The majority of the catenary structures are composed of steel H-section columns and crossbeams which are rigidly connected by knee braces to form self-supporting portal structures.

This type of construction for electrification structures has the following advantages.

1. Low cost of steel per pound.
2. Ease of detailed design and simplicity of shop details. These were made in the railroad's drawing room which saved time and expense.
3. Ease, speed and low cost of fabrication.
4. Simplicity of construction with resulting good appearance.
5. Ease of painting with resulting economical maintenance.
6. The H-section has greater strength in one direction than the other and in this way can be used to take care of all the varying load conditions which arise.

In the five-mile section between Reading Terminal and Wayne Junction there are four or more tracks on an elevated structure. Due to restricted right-of-way it was necessary to carry the transmission circuits on masts instead of on the catenary columns. This necessitated the use of fabricated trusses instead of H-section crossbeams.

These masts were located so that there would be adequate clearance between the wires and any present or future buildings on the properties adjoining the right-of-way.

In outlying sections the structures have H-section columns and H-section beams. However, in cases where the crossbeam spans five or more tracks, channel type beams were used. These beams are composed of two channels laced top and bottom and placed with webs vertical and bolted to the flanges of the columns.

For single-track lines self-supporting columns with brackets for supporting the catenary are used on tangent track. On curves the same arrangement is used with the exception that the columns are back guyed.

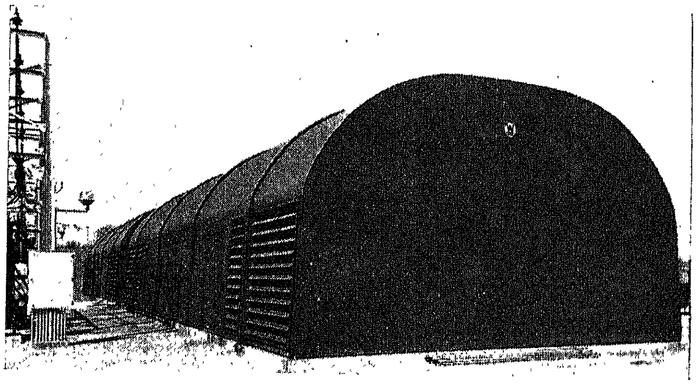

Fig. 4—Outdoor Type Frequency Changer

At the outer face of many overhead bridges, which generally were so low as to make it necessary to grade the contact system down to pass under them, a 5-in. standard I-beam was supported by means of brackets. This I-beam in turn carried post type insulators to which were attached the contact system messengers.

On the faces of these overhead bridges it was necessary to provide protective screens so that the contact system passing underneath would be inaccessible to persons on the bridge.

*Signal Bridges.* At signal locations, in sections where there were three or more tracks, the color light signals were placed on the catenary structures. Instead of providing special and heavier structures at such points, the only modifications to accommodate signals were the addition of walkways, signal supports and platforms to the standard catenary structures. The beam type of structure, however, was changed from H-section beam to channel beam in the cases where signals are carried. On trusses the walkways and signal supports, etc., were easily attached by means of J-bolts.

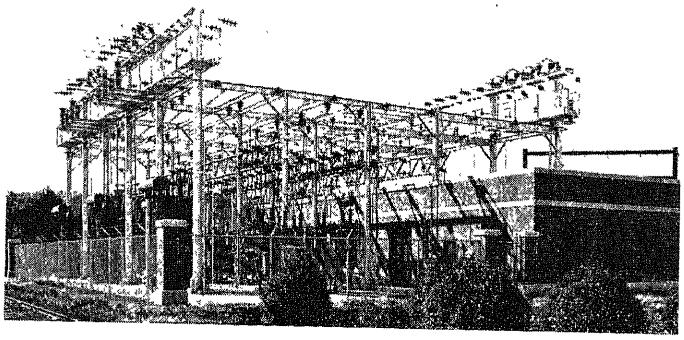

Fig. 5—Typical Transformer Substation

*Foundations.* Reinforced concrete foundations of 1-2-4 mix were used for the structure columns. In these, bolts were provided to secure the columns to the foundations.

In many locations within the limits of Philadelphia, it was necessary to design special foundations, the outlines and dimensions of which were largely dictated by adjacent walls, buildings and other structures which existed prior to electrification. These special cases presented many unusual and somewhat difficult problems in design and construction.

The foundations are of two general gravity types, *i. e.*; one providing column fixity both parallel and normal to track, the other giving fixity only in a plane parallel to track. The latter type which was in the majority was very economical both in materials and labor. Due to its narrow width it did not require shoring of adjacent tracks.

In the construction of the foundations, steel panel forms were used. These had a templet at top to hold the foundation bolts securely in their proper position while the concrete was poured and hardening. These forms which were used many times over, were found to be very economical and will continue to be used on future construction.

When hard rock was found at a structure site either a side bearing type of foundation or a type with ragged and wedged foundation bolts grouted into the rock was used. The grouted foundation bolts were used only in solid rock and in such instances the concrete piers were cast around them after grouting.

*Design.* All structures were designed on the basis of standard Class B loading, *i. e.*; ½-in. ice with 8 lb. per sq. ft. wind on wires and 12 lb. per sq. ft. wind on flat surfaces. Also alternate loadings of 20 lb. per sq. ft. on bare wire and 30 lb. per sq. ft. on flat surfaces.

Broken wire loads of 1,000 lb. on column or of 2,000

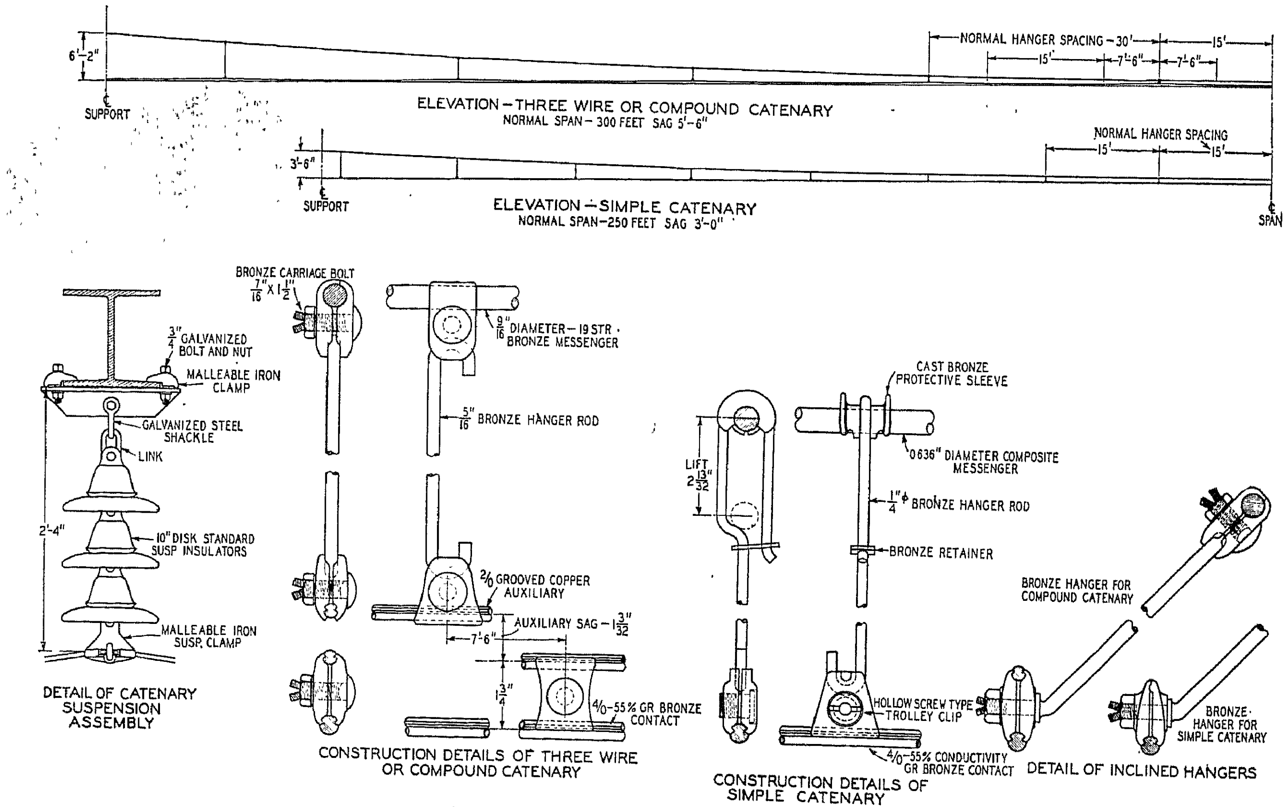
6'-2"
℄ SUPPORT
NORMAL HANGER SPACING - 30'
15'
15'
7'-6"
7'-6"
ELEVATION - THREE WIRE OR COMPOUND CATENARY
NORMAL SPAN - 300 FEET SAG 5'-6"
3'-6"
℄ SUPPORT
NORMAL HANGER SPACING
15'
15'
ELEVATION - SIMPLE CATENARY
NORMAL SPAN-250 FEET SAG 3'-0"
℄ SPAN
3/4" GALVANIZED BOLT AND NUT
MALLEABLE IRON CLAMP
GALVANIZED STEEL SHACKLE
LINK
2'-4"
10" DISK STANDARD SUSP INSULATORS
MALLEABLE IRON SUSP. CLAMP
DETAIL OF CATENARY SUSPENSION ASSEMBLY
BRONZE CARRIAGE BOLT 7/16" X 1 1/2"
9/16" DIAMETER - 19 STR. BRONZE MESSENGER
5/16" BRONZE HANGER ROD
2/0 GROOVED COPPER AUXILIARY
AUXILIARY SAG - 1 3/32"
7'-6"
1 3/4"
4/0-55% GR BRONZE CONTACT
CONSTRUCTION DETAILS OF THREE WIRE OR COMPOUND CATENARY
CAST BRONZE PROTECTIVE SLEEVE
LIFT 2 13/32"
0636" DIAMETER COMPOSITE MESSENGER
1/4"φ BRONZE HANGER ROD
BRONZE RETAINER
HOLLOW SCREW TYPE TROLLEY CLIP
4/0-55% CONDUCTIVITY GR BRONZE CONTACT
CONSTRUCTION DETAILS OF SIMPLE CATENARY
BRONZE HANGER FOR COMPOUND CATENARY
BRONZE HANGER FOR SIMPLE CATENARY
DETAIL OF INCLINED HANGERS

Fig. 6—Typical Catenary Details

lb. on beam were also used. Under the above loadings a maximum fiber stress in steel of 25,000 lb. per sq. in. was allowed in net section.

Reinforcing steel and concrete is stressed to 20,000 and 800 lb. per sq. in., respectively.

Soil pressures of 4,000 lb. per sq. ft. on cinders and 5,000 lb. on earth was allowed.

## Design of Transmission Lines and Catenary System

*Transmission Line.* Bearing in mind the possibility of future "through" electrification to New York, Bethlehem and Reading, provision has been made on the main line catenary structures for the installation of a double-circuit 66,000-volt transmission line. At present the only transmission lines carried are the 24,000-volt feeders or "balance wires" for the three-wire system. On single-track branches, only one of these feeders is used, and on two and four track sections of the railroad, two feeders are installed. All catenary columns are connected together by a ground wire, which is clamped to the pole cap with a special fitting. The ground wires serve manifold purposes; namely, to protect against lightning, to ground the structures, to assist the trolley rail circuit as regards conductivity, to reduce inductive interference and to prevent excessive deflection of the structures in case of a broken transmission or catenary wire. Following the usual practise in railroad electrification, all lines have been heavily insulated. On the 12,000-volt catenary lines, three standard 10-in. suspension units are used in series, and on the 24,000-volt feeders, four units are used. It is proposed to install six units at each suspension point on the 66,000-volt circuits, and all clearances have been made sufficient to accommodate this insulation.

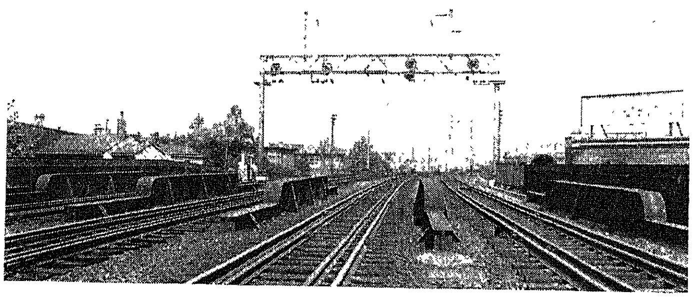

FIG. 7—TYPICAL 4-TRACK SECTION COMPOUND CATENARY

*Catenary System.* From Reading Terminal in Philadelphia to West Trenton on the New York line, the catenary system is of the conventional compound three-wire inclined type. The messenger is a 9/16-in. diameter bronze cable, the auxiliary is a 2/0 grooved copper wire, and the contact is a 4/0 bronze wire. The catenary supports for this type of construction are 300 ft. apart on tangent tracks and wind steadies are placed at every structure on tangent except where shelter is provided by adjacent high buildings, etc.

On all other electrified tracks, simple two-wire inclined catenary is used comprising a 0.636-in. diameter composite bronze and copper messenger and a 4/0-grooved bronze contact wire suspended on tangent track from the messenger by lifting loop hangers. Tangent structure spacing is 250 ft. and no steadies are used on the contact wire. This is the first installation of long span steel structure simple catenary in this country and its use has resulted in simplicity and ease of erection and maintenance, and superior quality of current collection. The simplicity and advantages of the air gaps used with this type of catenary are also very gratifying.

In the table below are shown the different wires used on the Reading electrification.

All catenary and transmission lines were designed to take a stress well below the elastic limit when loaded with ½-in. radial coating of ice at 0 deg. fahr. The variation in alinement of the inclined catenary due to changes in temperature was calculated prior to erection, and where it appeared that excessive lateral movement would occur, steadies were placed on the contact wire. It was found that the greatest movement occurs on the compound catenary on curves where the hanger slope is about 45 degrees.

The hangers, clips, steadies, etc., are all bronze of a composition highly resistant to corrosion. In compound catenary, the hangers are clipped both to the main messenger and auxiliary messenger on tangent track, the hangers alternating with clips which fasten the contact wire to the auxiliary. On the simple catenary, loop hangers are used on tangent track, a protecting sleeve being placed over the messenger at each point to eliminate any possibility of wear. In every second span of simple catenary on tangent a feeder jumper of flexible cable joins the contact wire to the messenger; the

| Size wire | Purpose | Material | Conductivity cm. | Weight lb. per ft. | Ultimate strength | Normal tension | Maximum working tension |
|---|---|---|---|---|---|---|---|
| 9/16-in. diameter | Messenger | Bronze stranded | 34,000 | 0.744 | 19,750 | 3,820 | 7,500 |
| 0.636-in. diameter | Messenger | Composition bronze and copper | 211,600 | 0.935 | 19,100 | 4,340 | 7,675 |
| 4/0 | Contact | Bronze (grooved) | 116,400 | 0.641 | 10,200 | 2,500<br>3,000 | 4,170<br>4,670 |
| 2/0 | Auxiliary | Copper (grooved) | 133,000 | 0.403 | 5,220 | 1,200 | 2,200 |
| 7/16-in. diameter | Messenger (yards) | Bronze stranded | 20,900 | 0.457 | 12,150 | 2,490 | 4,830 |
| 2/0 | Feeder and ground wire | Copper stranded | 133,000 | 0.411 | 6,270 | 830 | 2,350 |
| 4/0 | Feeder and transmission | Copper stranded | 211,600 | 0.653 | 9,970 | 1,320 | 3,140 |
| No. 1 | Signal circuit | Copper stranded | 83,700 | 0.255 | 3,740 | 520 | 1,820 |

loop hangers, therefore, are required to carry only a negligibly small current. The inclined hangers on curves are identical on both the simple and compound catenary. They comprise a 3/8-in. diameter rod, upset to 7/16-in. at the lower end, and provided with a shoulder to receive the contact wire clips.

The car storage yards and the Reading Terminal are wired with chord catenary, consisting of a 7/16-in. messenger and a 4/0 contact wire. In all wired crossovers, and at sectioning points in the main line, air breaks are installed. Wood stick insulators are used only where it was not possible to use air breaks.

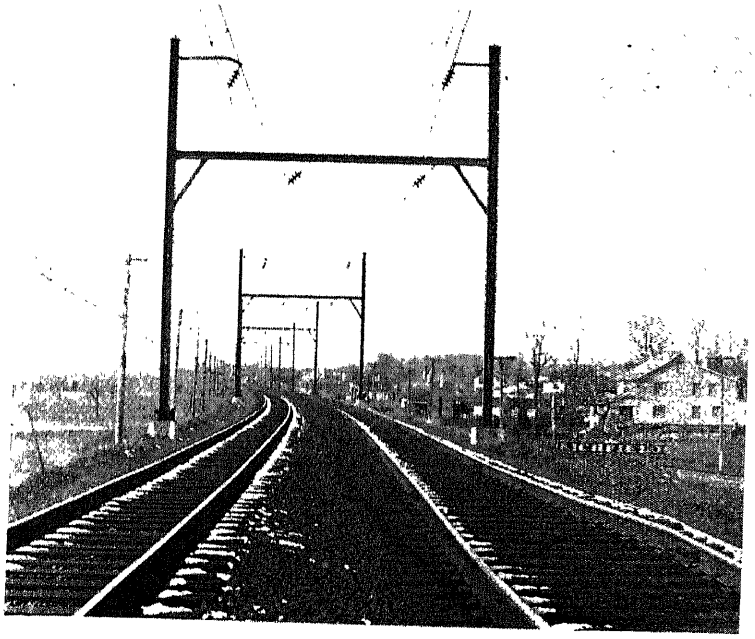

FIG. 8—TYPICAL 2-TRACK SECTION SIMPLE CATENARY

Where highway bridges pass over the tracks, the catenary is carried on rigid post type insulators erected on brackets on each side of the bridge. A minimum clearance of 6 in. from the messenger to ground is permitted at certain points, but the desired standard clearance is 9 in. or more. The standard contact wire height is 22 ft. and in approaching overhead bridges, the gradient in the contact wire is kept down to 0.5 per cent relative to the track.

Prior to erection of the contact line, all stringing tensions and hanger lengths were worked out, so that field adjustments were reduced to a minimum. Where inclined catenary is used, the stringing tension on curves is less than on tangent; to take care of this, the messenger was snubbed on every curve during tensioning; then when the contact wire load was added, the messenger assumed its proper tension on both tangent and curved track, and the snubs were removed.

## RAIL RETURN SYSTEM

*Traction Bonds.* The standard rail section of the Reading System is a 130 lb. head-free type. The joint is one developed for use with this rail and the joint and rail have a cross section not particularly adapted to the application of all types of bonds as the bead on the joint projects a considerably greater distance than is the case with the usual rail joint.

The traction bonds selected for installation on this system are of No. 1 A.W.G. gas weld 8-in. straight type.

*Impedance Bonds.* On all main line tracks the rails are a part of the 100-cycle a-c. track circuit. In order that the rail return may be continuous, impedance bonds having a continuous rating of 100 amperes per rail are provided around the insulated joints which permit the traction power to flow but offer high impedance to the flow of signal current.

*Special Bonding.* In order effectively to ground each structure, all structures wherever possible are tied together by means of ground wires, the ground wires being bonded to rail through impedance bonds, usually at the end of every other track section so as to provide maximum broken rail protection.

Cross bonds or bonds connecting together the rails of all bonded tracks, are installed at frequent intervals. Insulated 2/0 cable is used for these bonds and, as in all cases wherever there is any possibility of maintenance of way forces disturbing the installation, a covering of fiber impregnated planking is installed directly over the cable and the whole covered with earth.

### MULTIPLE UNIT CARS

| Type of car | In service | Under construction | Total | Seating capacity | Baggage space | RPO space |
|---|---|---|---|---|---|---|
| Motor | 61 | 28 | 89 | 86 | 0 | 0 |
| Motor | 7 | 2 | 9 | 62 | 17 ft. 1 in. | 0 |
| Motor | 2 | 0 | 2 | 38 | 16 ft. 8½ in. | 17 ft. 1 in. |
| Trailer | 20 | 0 | 20 | 84 | 0 | 0 |
|  | 90 | 30 | 120 | Total |  |  |

The trailer cars which were converted from steam cars are used only in rush hour trains and in the ratio of one trailer car to three or more motor cars. Due to the fact that these rush hour trains are largely express runs, the schedules and motor heating are not greatly effected by this method of operation. All trailers are equipped with electric heaters, bus connectors, cab signals and a control cab at both ends, so as to give maximum flexibility of operation.

Each motor car is a complete unit, equipped with motors, storage battery, air compressor, cab signals, and a control cab at each end. On the 30 motor cars under construction the cab signal equipment is being omitted, but provision is being made for its installation when needed.

A careful study was made of the use of aluminum alloys and the economies involved due to the resultant weight savings. Alternate bids were obtained from the car builder on the use of aluminum in the various parts and resulted in a saving of 6,640 lb. per car. The estimated annual saving in power cost due to this weight reduction was considerably more than the interest on the additional investment. The trucks, side-sheets, underframing and all stress carrying members are of steel construction.

The seating arrangement consists of 37 cross seats spaced 33½ in. from center to center to provide ample leg room, and three longitudinal seats, each seating four people.

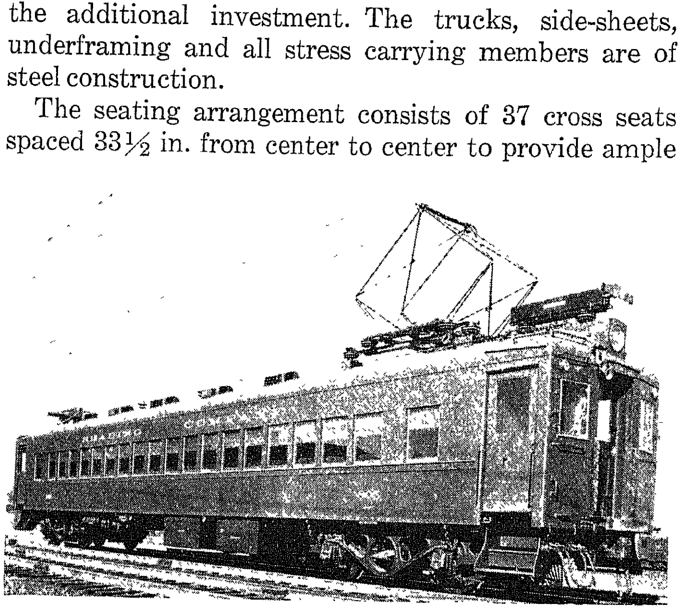

Fig. 9—Multiple Unit Car

The interior of the car is painted three-tone gray, striped in blue and gold. The hardware fixtures, baggage racks and light fixtures are of a sanded nickel finish, giving the cars a clean, bright appearance. Brass window sash is used which eliminates sticking and adds to the appearance of the car.

There are no signal or emergency cords passing through the car, the signals being electrically operated by push buttons. The emergency cord is located in the vestibules, but is accessible from the inside of the car. There are two push buttons for the conductor's signal buzzer, located in the interior of the car, one over each vestibule end door, and one under each corner post of the car. The latter are provided so that the conductor can stand on the station platform and signal the motorman to start, just before he boards the train, thus saving a little time at each stop.

*Motors and Control.* Due to the short runs and severe grades it was desirable to obtain as large a traction motor as possible and still meet the space and other design limitations. Therefore, new designs were developed by each manufacturer and used on the cars. These new designs produced a motor with a one hour rating of 300 hp. and a continuous rating of 240 hp. The improvement over prior designs is brought about by using a larger number of poles, permitting a low flux density, which in turn produces better commutation. In addition, the weight per horsepower is considerably less than on previous motors, while exceptionally high values of efficiency and power factor have been made possible.

An accelerating rate of 1.25 mi. per hr. per sec. is obtained in service with a normal voltage of 11,000 at pantograph and with full seated load, resulting in a car weight of approximately 70 tons. This weight is divided 60 per cent on the motor truck and 40 per cent on the trailer truck, resulting in a low adhesion of 10.4 per cent and consequently very little wheel slipping.

This accelerating rate is the highest yet attained on a-c. equipment, and even though it is less than generally used on d-c. multiple unit equipment it results in a higher schedule speed in a service in which the average length of run is over 0.8 miles. For example, although it takes 24 seconds for a car to reach 30 mi. per hr. it only takes 60 seconds to reach 50 mi. per hr. Another example of the sustained horsepower of these motors is the fact that a 2-car train has a balancing speed of 56 mi. per hr. on a grade of 1.13 per cent. On level tangent track the balancing speed is between 75 and 80 mi. per hr., depending on the length of train; however, the equipment is restricted to a maximum speed of 72 mi. per hr.

The main controller is of the automatic accelerating type located under the car and remotely controlled through a 32-volt circuit from a master controller in the cab. The master controller has the dead-man's release which is further equipped with a foot pedal to hold it in position so that the motorman can have both hands free if desired.

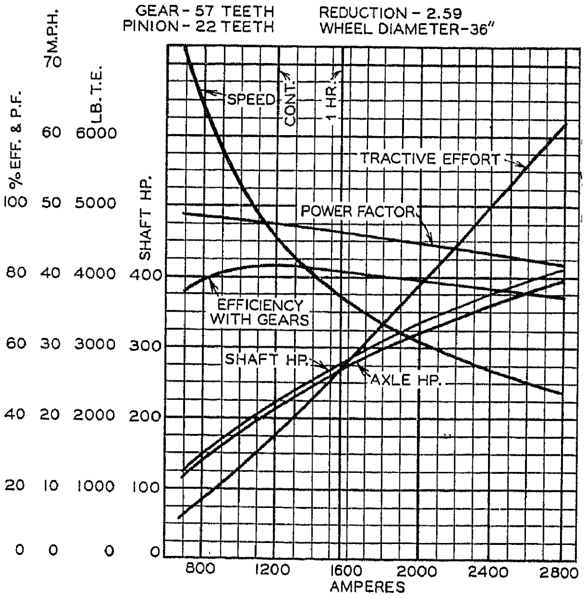

Fig. 10—Motor Characteristic Curves

170/340-volt, single-phase, 25-cycle railway motor. Characteristic curves on 170 volts, 25 cycles

*Trucks.* Eighty cars are equipped with Taylor flexible trucks and 20 with Commonwealth trucks. The Taylor truck has been used before on freight cars and on some experimental installations of passenger cars and locomotive tenders but this is the first time it has been used on electric cars. Its advantages are, greater flexibility and lighter weight.

## New Developments

One outstanding development of the car is the bus connector. This connector makes it possible to connect all pantographs together, thus providing power on all cars when only one or two pantographs are in service. It is expected that the use of this device will show considerable savings in pantograph shoe and trolley wear. It has already shown its value in making it possible to continue a trip with power on *all cars* after pantographs have been damaged on several of the cars in the train.

A magnetic door latch has been developed and installed on the body end doors of the cars. This latch holds the doors open during the time a train is coasting to a stop and standing in a station but automatically releases the doors upon the starting of the train. When released, the doors are closed gently by an ordinary air cushion door check. This device insures the doors being open a minimum length of time, thus reducing drafts on the passengers and conserving heat in the cars.

Double thermostat control of the electric heaters is used, one thermostat being set at 50 deg. fahr. and the other at 65 deg. fahr. These thermostats are so connected that when the engineman has his controller plug in the master controller the 65 deg. thermostat is connected and when he leaves his cab, as during short lay-overs in the terminal, the 65 deg. thermostat is disconnected and the 50 deg. thermostat is cut in. This makes it possible for the cars to be kept moderately warm during the lay-over. Of course, when the car goes into storage and the pantograph is lowered, the heat is all cut off. Switches are also provided for cutting off the heat during warm weather.

The motorman is also provided with a "train heat" switch which enables him to change all thermostats in the train from the 65 deg. to the 50 deg. setting at will. Operating rules require him to cut off this train heat switch ten minutes before reaching his terminal, unless the equipment is going to remain in service. This results in a considerable saving in heating power cost.

A new design of ventilating system is used which insures sufficient air being delivered to the motors and transformer at all times. Special attention was given to the cleaning of the air and to keeping the velocity low. A "no blower cut-out" is installed to prevent the operation of a car in case of a failure of the ventilating system.

## Interchangeability of Apparatus

Although the motor and control equipment was furnished by three different manufacturers, and two different types of trucks were used, it was possible by careful design, to build all the cars from one set of drawings and use one schedule of hangers. The traction motors and air brake rigging are so designed that it is possible to interchange the two makes of trucks.

Very careful attention was given to the arrangement of apparatus on the underside of the car so as to simplify inspection and maintenance.

The flexible connection through which the air passes to ventilate the motors is designed so that it automatically disconnects itself when the motor is removed and then automatically goes into place when the motor is replaced.

A spring motor nose suspension is used which can readily be removed and the motor can be dropped out of the bottom of the truck by a special pit jack in the shop without it being necessary to remove the trucks from the car. The motor can also be lifted out of the top of the truck in the ordinary manner if desired. A wheel pit has also been built into the shop so that wheels can be dropped without removing either the truck or the motors. This eliminates the necessity of disconnecting the motor leads when changing wheels. These pit jacks can also be used to remove the transformer, compressor and other apparatus.

## Storage, Inspection and Repair Facilities

The storage yard is located at Wayne Junction and is designed to accommodate 86 cars at present and 160 ultimately, keeping one track open as a run-around track.

The new shop is located near the center of the storage yard and is provided with five tracks, three for light inspection and two for heavy repairs. All tracks are long enough to accommodate 4 cars and are arranged so that the cars can be routed progressively into one end of the shop and out of the other. This gives the shop a capacity sufficient to maintain over 200 cars. Room is provided for an extension of 125 ft. on the heavy repair bay for the maintenance of future electric locomotives.

## Other Improvement Work Done Concurrently with Electrification

As in all terminal electrifications, extensive improvements were made concurrently with electrification. These consisted of elimination of grade crossings; obtaining additional clearances at points where overhead bridges or other obstructions did not give sufficient clearance for installation of the overhead wires; building new suburban car storage yards at outlying points; a new car storage yard for storing cars at Wayne Junction during the middle of the day; the change and modernization of the signal system in the electrification territory and the placing in cable of communication circuits. In certain territory where right-of-way was restricted, underground ducts were provided for signal and communication cables. Nine new stations were also built at various points in the suburban territory. The cost of all these associated improvements exceeded the cost of the electrification construction proper including rolling stock.

## Inductive Coordination

It was realized that electric operation of the railroad would necessitate coordination of the electrification and communication facilities, both belonging to the railroad and those of commercial companies, therefore, the railroad's plans were from the beginning discussed with representatives of the telephone and telegraph companies, and this feature was kept in mind during the design of the electrification. A series of cooperative tests was made before the start of electric operation.

From results of over a year of operation there has been no trouble due to inductive disturbances in either the railroad's communication facilities, or those of other companies.

### Construction Features of the Work

The installation of the work in its entirety, with the exception of buildings for car shop and substations, was done by the railroad's construction forces organized for the purpose and under the supervision of the electrical department. The construction features of such an installation are complex and expensive, and made difficult due to the necessity for maintaining traffic at all times without delays. After surveys were made and plans issued to the field forces, the first step was the installation of foundations for catenary structures. Because of congested right-of-way, particularly between Reading Terminal and Wayne Junction, where the railroad is on an elevated structure, and where in many cases the center of the outside tracks is only seven feet from the right-of-way line, the installation of foundations was particularly difficult and expensive. It was necessary to go to extensive shoring of the tracks in order to maintain traffic, this feature for this five miles of railroad costing $40,000 alone. The concrete for the foundations was all mixed and poured from concrete mixing plants installed on cars and operated in work trains. Water was supplied to the mixer from tank cars insulated against cold and heated in winter with steam from the engine. Approximately 35,000 yards of concrete was used in the work.

Steel structures were all erected by means of a derrick car, purchased for the purpose, which could be operated on one track without obstructing traffic on adjacent tracks. Steel was shipped from the fabricator in cars loaded in the order in which it was to be installed; thus eliminating rehandling on the job.

Transmission wires were strung by means of teams of horses in the customary manner for power lines. The messenger, auxiliary and trolley cables were strung by using reel cars from which the cables were led out through temporary sheaves attached to the bottom of the suspension insulator strings. All wires, fittings, etc., were installed from tower cars by means of work trains, and all wire and fittings were designed, assembled, and marked for the span or the structure where they were to be installed and delivered to proper location. This scheme resulted in minimizing the time required in the field, which is absolutely essential due to the high cost of work train service and the interference with traffic by the work trains.

The substation steel and apparatus were installed in the customary manner. The supervisory control equipment was installed by the substation construction forces.

Concurrently with the above the bonds were being installed, wire crossings eliminated or altered, signals and communication changes made, additional yards installed, tree trimming attended to, etc., etc.

As soon as power was available and a section was completed, everything was thoroughly tested out with particular reference to obtaining proper selectivity on the circuit breakers, and actual short circuits to ground were placed on every circuit of the network. The system of relaying was new and some adjustment of relays was found necessary.

Such a construction program requires close cooperation from the purchasing, stores, signal, telegraph, engineering and motive power departments and particularly the operating department. During a considerable part of the time, there were as many as 20 work trains in use on the work.

Several months before the start of operation, the training of the steam enginemen who were to operate the new equipment; the inspectors and shop forces who were to maintain it, and the power dispatching and electrification maintenance forces, was started. Instructions in operating and safety rules were issued, and all electric trains on all branches were placed in operation simultaneously on the morning of July 26, 1931.

### Results

Electric operation has now been in effect over a year. In spite of speeding up of schedules by 20 per cent and an increase in trains and train miles of approximately 100 per cent, the cost of operation is substantially lower than was the case for the service in the same territory by steam. A continual loss in traffic has been changed into an appreciable increase, and as a result of this showing, the railroad management recently authorized the electrification of the suburban service on its Norristown Branch from Philadelphia to Norristown. This service, along with the Chestnut Hill Branch, will go into operation about January 1st 1933.

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## Discussion

**J. S. Moulton:** There are three matters covered in Mr. Wright's paper, in addition to the technical description of the electrification, which deserve emphasis.

The first of these is the problem confronting all railways whether local, interurban or steam. The increasing competition from other forms of transportation has severely reduced both passenger and freight traffic of the railroads. All roads have reduced operating expenses drastically in an effort to offset reduced revenues. With a large part of the total costs tied up in permanent capital, and, therefore, not susceptible to reduction, there is a limit beyond which operating cuts are not effective. Stimulation of traffic and modification of the basic character of the system, are additional methods of endeavoring to maintain profitable operations. An experiment with fares as a means of stimulating street car travel which at the time of writing is being tried at Bakersfield, California, may be of interest. The existing tariff which has been in effect for several years is a 10c. cash fare, 7 tokens for 50c., or a $1.00 weekly transferable pass. The system has not been earning more than pocket operating expenses for the last year, but before deciding upon abandonment, a drastic experiment is being tried. For a two-month period free passage is being given between the hours of 9:30 a. m. and 3:30 p. m., Sundays and holidays excluded. Following this period, a 5c. fare for all hours will be tried out for a period of three months. After that, it is planned to restore the former schedules if experience in the meantime does not indicate the wisdom of some other tariff. The merchants are featuring the free ride privilege with their advertising. While it is too early to tell what the effect of the experiment will be, the total number of passengers during the first month of this free ride period has been over three times the number for the preceding month, and the business of the merchants has improved.

The second feature of Mr. Wright's paper describes the use of visual cab signals in place of more expensive full automatic control. According to Mr. Wright, the use of cab signals has been fully justified by the absence of accidents. While safety is of course the primary requirement, it is important to keep both investment and operating expenses at a minimum. How much better it would be if the railroads with their vast store of operating experience, and with new methods constantly being developed, could be free from the unelastic requirements now prescribed by regulatory bodies, the experience of which is frequently theoretical rather than practical.

The third point of general interest relates to the cooperative manner in which the rate for power was worked out between the Reading Company, and the Philadelphia Electric Company, the rate providing that after the railroad load reaches a certain fixed amount that the charge will be based upon cost of service including a fair return on the property required to serve the railroad. One of the reasons that an electric utility can give service more cheaply than isolated plants is that through serving a diversity of loads, its generating capacity can be operated at a higher load factor than could a number of separate and isolated plants. The agreement to compute the rate on cost of service is in line with the modern tendency toward giving greater weight to the cost elements of service and further indicates the increasingly cooperative spirit between different kinds of utilities. The arrangement between the railroad and the electric utility for joint use of right-of-way, and for service at cost, is a step in the right direction toward greater coordination of utility services from which the public will be the greatest benefactor.

**A. J. Schoch:** The complete suburban electrification of the Reading Company was engineered and installed by Mr. Wright and his staff. While established practises were adhered to in general, they did not hesitate to depart from such practise when their objective necessitated doing so. Operation to date has proved the wisdom of such departures. The most striking example was the installation of simple two-wire catenary over a large part of the electrified tracks. In this country it has been universal practise to install some form of compound catenary for all main line and suburban electrifications. Of course, the low conductivity required with the high-voltage, single-phase system makes the simple two-wire catenary quite attractive. This form of catenary is far superior from the standpoint of simplicity and ease of erection and maintenance.

Furthermore, experience has shown that the quality of current collection is also better. Experience to date has resulted in the decision to install this type of catenary on the Norristown and Chestnut Hill lines which are now being electrified. The results obtained will, no doubt, lead to the adoption of simple catenary for future heavy traction electrifications.

A very careful study was made of the use of aluminum alloys in both the electrical equipment and the car body. However, its application was limited to non-stress carrying members. Even with this limitation, the Reading car ranks first, from the standpoint of weight per seat or weight per continuous horsepower, among modern high voltage multiple unit cars either alternating current or direct current.

Greater effort and study were undoubtedly given to the location and arrangement of equipment underneath the car than was ever attempted heretofore. This not only simplified the original installation but has made the job of inspecting and maintaining the equipment much easier. Furthermore, in spite of equipment being supplied by three different manufacturers complete interchangeability of apparatus was secured.

A number of novel features were introduced on the car. The most outstanding of these was the high-voltage bus line connecter. This connecter gives many operating advantages and the results have been very successful; the coupler itself requiring practically no maintenance.

Due to severe grades and short runs encountered on the Reading system, the service is unusually severe. The equipments designed to meet this service are capable of accelerating the cars at 1.25 miles per hour per second up to a speed of 30 miles per hour and have a balancing speed in excess of 70 miles per hour. Consequently, in average suburban service these cars are capable of making the highest schedule speed of any suburban cars in this country.

# Electrical Operation on the Cascade Division of The Great Northern Railway

BY J. B. COX*
Associate, A.I.E.E.

THE electrification of the Great Northern Railway main line between Skykomish and Wenatchee, 73 route miles, has been quite fully described in a number of articles published in technical journals during the past three years, rendering it unnecessary to repeat a detailed description of the installation here. The electrification was carried out in conjunction with the building of a new tunnel 7.79 miles long and a relocation of approximately 17 route miles of troublesome track and other minor improvements, aggregating an expenditure of approximately $25,500,000. All these improvements were placed in operation at about the same time so that there has been no opportunity to make a direct and segregated comparison of operating expenses which would indicate definitely the advantages of each improvement separately.

The completion of this new tunnel was the second undertaking of that nature in the history of the Great Northern Railway's route across the precipitous Cascade range. The original route, which was placed in operation in 1893, went over the range through Stevens Pass at an elevation of 4,059 feet. It was possible to keep the maximum grade at a limit of 2.2 per cent up to elevation 3,382 feet on the eastern slope, and to elevation of 3,126 feet on the western slope. These points were approximately 2.7 miles apart by direct line through the mountain or 4.5 miles over the Pass.

A tunnel between these points was considered at the time but it would have cost more and taken much longer to build, two very important items in those days, so the line was built through the Pass. This was done by increasing the ruling grade to 4 per cent and resorting to an eight point switchback, involving approximately 12 miles of track.

As had been foreseen, this switchback became the proverbial bottle-neck of the line and with the natural increase of traffic, its capacity was soon reached. This was particularly so during the winter months when there was apt to be an aggregate fall of any where from 50 to 100 feet of snow, and at a rate as high as 8 to 10 inches per hour at times.

To overcome these difficulties and to improve the service, the construction of a 2.63-mile tunnel was begun in 1897 and placed in operation in 1900. This tunnel ran in a perfectly straight line at a constant grade of 1.695 per cent eastbound, cut out the entire switchback and eliminated 2,332 degrees of curvature and all grades in excess of 2.2 per cent. This improvement shortened the route approximately 9 miles which reduced the running time of all trains about two hours with a corresponding decrease in operating expenses.

With a further increase in traffic the ventilation of this tunnel became so unsatisfactory with the operation of coal burning steam locomotives that the tunnel and tracks at each end were electrified. The three-phase system was selected for this installation largely because of its ready adaptation to regenerative braking and was the first and only application of this system in America, as well as the first regenerative braking on a steam railroad. This installation and the necessity for same were fully described in a paper by Dr. Cary T. Hutchinson,† the consulting engineer.

The electrical operation of this tunnel was begun in July 1909 and the three-phase equipment satisfactorily met the original requirements and was continued in service until March 1927 when it was replaced by the present system.

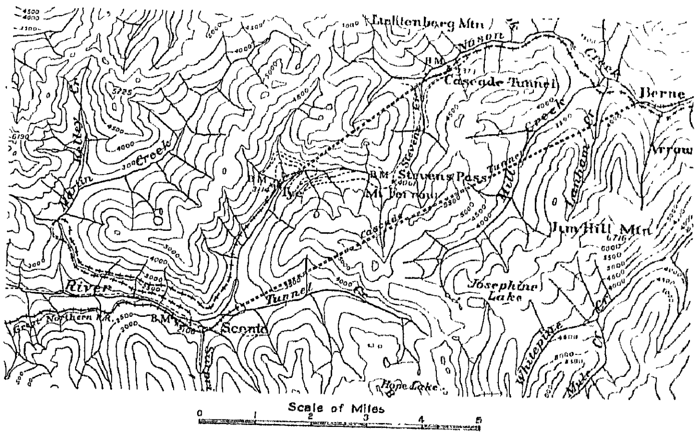

FIG. 1—TOPOGRAPHICAL MAP SHOWING LOCATION OF THE OLD AND NEW ROUTES

The only notable modification of the equipment was the installation of the necessary wiring and switches for arranging for a concatenated connection of the traction motors which provided for a running speed of 7½ miles per hour in addition to the 15 miles per hour originally selected. This was done in the latter part of 1923 when the division point was removed from Leavenworth to Wenatchee (Appleyard) which increased the length of the freight run from 109.3 miles to approximately 132 miles, and it was desired to take the entire train through the tunnel at a single trip instead of in two trips as was necessary at a speed of 15 miles per hour, owing to the limited capacity of the Tumwater power plant.

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*Presented at the Pacific Coast Convention of the A.I.E.E., Vancouver, B. C., August 30-September 2, 1932.*

†*The Electric System of the Great Northern Railway at Cascade Tunnel*, A.I.E.E. TRANS., 1909, Vol. 38, p. 1281.

At the beginning of the electrical operation, the freight trains did not exceed 1,600 tons trailing so that three of the 115-ton electric units were used to take this train with the road steam locomotives, equivalent to about 450 additional trailing tons when being hauled at 15 mi. per hr., through the tunnel at one trip. With a gradual increase of the train weights it had been found necessary to cut the heavier trains and take them through in two trips, which caused a delay of about one hour. By using the half-speed connection it was possible to use four electric units per train and to take up to 2,200 tons trailing and the steam road locomotives through the tunnel at a single trip, without exceeding the capacity of the power plant.

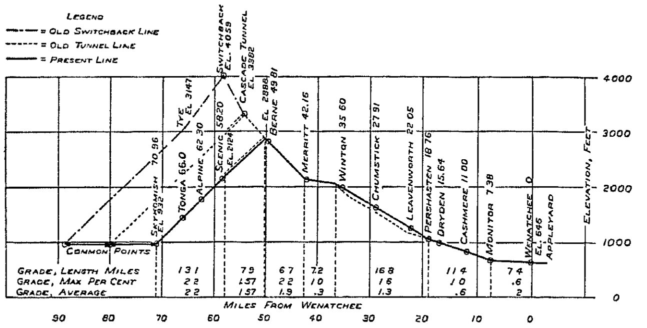

Fig. 2—Profile of the Old and New Routes, Skykomish to Wenatchee

This lessening of the total number of trips per day left the electric engine crews and the power plant idle a greater portion of the time with the logical result that consideration was soon given to the extension of the electrification from the west portal to Skykomish, a distance of approximately 21 miles, so that the electric units might be used to replace the steam locomotives used in the helper service on the 2.2 per cent grade up the west slope. A study of this plan indicated that quite a saving in operating expenses should result in addition to some saving in time as there would be practically no increase for electrical operating cost since the extended service would only increase the load factor without adding greatly to the crew hours paid for and the necessity for the stop at the west portal of the tunnel would be avoided. In the consideration of this extension it was realized that a new tunnel would undoubtedly be constructed within a few years, involving a new route which would result in the abandonment of at least nine miles of this proposed extension as well as the old tunnel electrification and that the expenditure for the extension should be kept at a minimum and that any additional electrical locomotives required should be capable of use on any desired change of route.

In the extended service the electric locomotives would operate as helpers to the regular steam road locomotives up the practically continuous 2.2 per cent grade for the 21 miles to the western portal of the old tunnel, at the entrance to which steam would be shut off, and the electric locomotives would have to take the train up the 1.695 per cent grade through the tunnel. The weight of trains would vary from 400 tons in the case of the lighter passenger trains to 2,500 tons for the heavier freight trains.

The available capacity at the power house was approximately 4,000 kw.

The constant speed characteristics of the three-phase locomotives with only two operating speeds were not best suited to meet these conditions and these, with the complications in the contact system owing to the necessity for the two overhead wires, made it unlikely that this system would be chosen in case the electrification should be extended beyond the mountain section.

The motor-generator type of locomotive which permitted of a combination of the most desirable features of the single-phase system and the d-c. system with which the speed might be varied to any degree necessary to conform to either the weight of train or available power or both, thus being well adapted to operation as helper to a steam locomotive, was chosen as being best suited to meet all the existing conditions. For the extension outlined, one double-unit class 1–D–1+1–D–1 motor-generator locomotive was originally ordered.

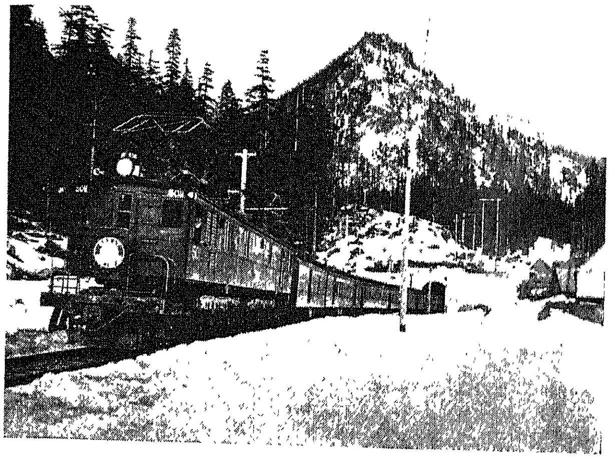

Fig. 3—Locomotive and Train Leaving Western End of New Cascade Tunnel

260-ton, 11,000-volt, single-phase, motor-generator type—Great Northern Railway

The three-phase generators at the power house were of liberal design, having sufficient excess capacity over the waterwheels to permit of their operation single-phase.

A few months after the equipment for this extension had been ordered and before it had been completed a decision was reached to construct a new tunnel 7.79 miles in length. The new route would leave the main line at Scenic on the west slope and join it again at Berne on the east slope, thus substituting 9.99 miles of new route for 17.67 miles of the old route with advantages as indicated in the following table of comparisons:

| | Old line | New line | Advantages of new line |
|---|---|---|---|
| Length in miles | 17.67 | 9.99 | 7.68 |
| Maximum curve degree | 10.00 | 6.00 | |
| Total curvature degree | 2,128 | 187 | 1,941 |
| Maximum grade | 2.2 | 2.2 | |
| Tunnel grade | 1.695 | 1.565 | |
| Summit elevation ft | 3,382 | 2,881 | 501 |
| Total rise westward | 546 | 45 | 501 |
| Total fall westward | 1,325 | 824 | 501 |
| Total length of snow shed-miles | 6 04 | | 6.04 |
| Total length bridges miles | 0.23 | 0.04 | 0 19 |
| Total length tunnels miles | 3.66 | 7.79 | |

The new line remained below the elevation of heaviest snow fall and traversed a route less subject to drifts and slides. A re-location of the line had also been surveyed between Winton and Peshastin which avoided some troublesome line in the Tumwater Canyon and reduced the maximum grade from 2.2 per cent to 1.6 per cent, the maximum curve from 10 degrees to 3 degrees and the total curvature 1,286 degrees and shortened the line about 1¼ miles.

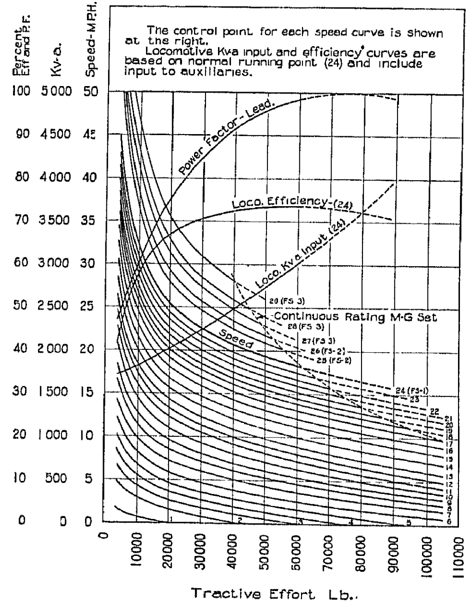

Fig. 4—Characteristic Curve of $1-C+C-1$ Locomotive Motoring

Locomotive characteristics 10,500 volts, 25 cycles

With these revisions of line in view and a definite decision to electrify the entire line between Skykomish and Wenatchee and to leave off the steam locomotives between these points, the character of the service was so changed as to make it desirable to consider some revision in the additional motive power that would be required for the extended service.

The 42 miles between Merritt and Wenatchee over the new route would safely permit speeds of 50 miles per hour whereas the line between Skykomish and Cascade Tunnel did not permit speeds in excess of 30 to 35 miles per hour and the new locomotive had been designed accordingly with a maximum safe speed of 40 miles per hour. With only 73 route miles electrified requiring so few locomotives, it was desirable to have all locomotives interchangeable between the passenger and the freight service and that any locomotive be capable of being operated in the same train with any other locomotive. The regular passenger trains operated over the line varied from 8 to 12 cars, aggregating from 700 to 1,000 trailing tons and the freight trains would ordinarily range between 2,500 and 4,000 tons trailing.

Fig. 2 shows a condensed profile of the present line and of the old lines. The ruling grade in each direction is 2.2 per cent, 10.5 miles of which is practically continuous, between Skykomish and the west portal of the new tunnel and 5 miles between Merritt and the east portal.

The grades range from 0.2 to 2.2 per cent, the average up grade for the line being approximately 1.29 per cent.

To meet these new conditions, a class 1−C+C−1 locomotive unit was proposed, the weight, etc., of which is given in the following table in comparison with the double unit locomotive supplied for the extension from Cascade Tunnel to Skykomish:

| Classification | 1 −C +C −1 | 1 −D −1 +1D −1 |
|---|---|---|
| Total weight | 539,000 | 715,400 |
| Weight on drivers | 426,200 | 550,000 |
| No of driving axles | 6 | 8 |
| Weight per driving axle | 71,030 | 68,750 |
| Weight on guiding axles | 112,800 | 165,400 |
| Weight per guiding axle | 56,400 | 41,350 |
| Length over couplers | 73 ft. 9 in. | 94 ft. 4 in. |
| Total wheel base | 58 ft. 8 in. | 78 ft. 11 in. |
| Rigid wheel base | 15 ft. 4 in. | 16 ft. 9 in. |
| Height over pantograph down | 15 ft. 3 in. | 15 ft. 10 in. |
| Number of traction motors | 6 | 8 |
| Tractive effort continuous rating | 60,500 | 88,500 |
| Tractive effort 30 per cent adhesion | 127,860 | 165,000 |
| Speed at continuous rating | 18.6 | 15.5 |
| Maximum safe speed mi. per hr | 50 | 40 |
| Number ordered | 8 | 5 |
| Secondary voltage transformer | 2,300 | 1,100 |

The 1−C+C−1 locomotives, designed particularly for the mixed service over the new line, will handle a 1,000-ton trailing train at 18.5 miles per hour on the 2.2 per cent grade and up to about 45 mi. per hr. on the 0.2 per cent, or averaging over the entire up grade portion about 28.6 mi. per hr., the average output of the motors being approximately 2,100 kw. or a rated load factor of 84 per cent. On the down grades the speed is limited to a maximum of 50 mi. per hr.

The regenerative features of the locomotive provide satisfactory control of the speed on the varying down grades to meet any conditions imposed by curvature, track conditions, or schedule requirements, ranging over the first 24 running points of the power controller, for each of which point graduated variations are possible through the 16 points on the braking controller, which regulates the traction motor field current.

Figs. 4 and 5 give the motoring and braking characteristics of this locomotive. Fig. 6 shows a schematic diagram of the control connections.

Two of the 1−D+D−1 locomotives were placed in the Skykomish-Cascade tunnel service in March 1927, two in the fall of 1928 and one early in 1929. The five locomotives of this class having been in service the equivalent of about 23 locomotive years.

Two of the 1−C+C−1 locomotives were placed in the Skykomish-Cascade tunnel service in September 1927, two others a year later and four were ordered in October 1929, nine months after the complete electrification had been placed in operation. These locomotives have now been in service about two years so that the eight units of this class have been in service the equivalent of 25 locomotive years.

Of this grand total of 48 locomotive years, approximately nine years were in the service between Skykomish and Cascade Tunnel as originally planned. This service consisted of helping the regular steam locomotive up the 2.2 per cent grade to the entrance of the tunnel, through which the grade was reduced to 1.695 per cent, making it possible to shut off the steam while in the tunnel.

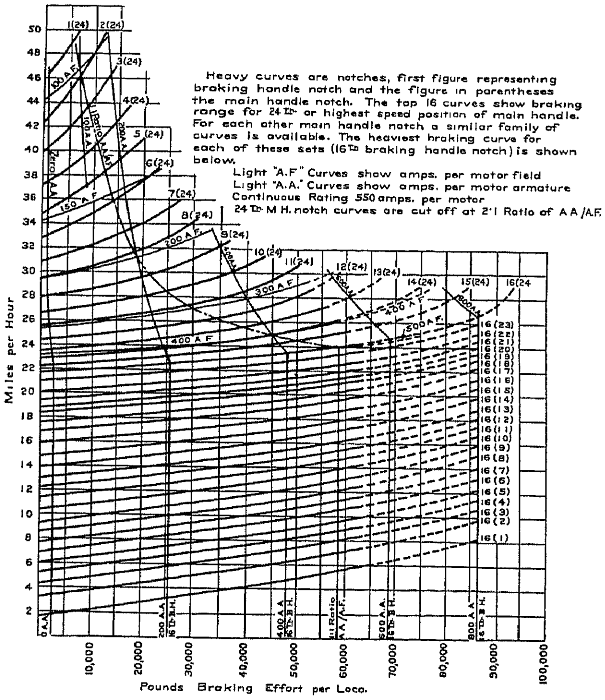

Fig. 5—Characteristic Curve of $1-C+C-1$ Locomotive Braking

The freight trains during 1927-1928, ranging from 2,500 to 3,500 tons trailing, were brought to Skykomish by two steam locomotives. Here, the rear steam locomotive was dropped off and replaced by two electric locomotives, one ahead of the steam road engine and one in the rear of the train. In the beginning, the rear locomotive was put at the extreme end of the trains but later it was found to be safer operation to place the rear unit about half to two-thirds back the length of the train. In the case of very long trains, with a powerful locomotive at each end, if for any reason the head engineer finds it necessary to stop suddenly and makes an emergency application of the brakes or should an air hose burst near the front end, the locomotive and cars so far away do not respond so quickly to the application and the front of the train is apt to stop before the brakes on the locomotive and cars at the rear have become sufficiently effective to prevent the momentum of the heavy locomotive from buckling the train at some weak spot, since the operator on the rear locomotive often has no warning of what is happening in time to shut off power until it is too late to prevent the damage. In descending grades by regenerative braking, it is also much safer and easier to have the two locomotives near together.

These heavy freight trains were taken from Skykomish to Cascade tunnel, 25 miles, in 1¾ hours whereas with steam operation from four to five hours were usually required. In the case of the passenger trains, one electric locomotive was placed ahead of the steam locomotive which helped propel the train, in accordance with requirements, to the entrance of the tunnel through which the electric took the train and engine unaided.

This operation was inaugurated in March 1927 and continued until the opening of the new tunnel January 12, 1929. The electrification work was completed between Berne and Wenatchee in November 1928, three months ahead of the completion of the tunnel. In order to break in this new line and to prepare for the inauguration of the new service, the steam locomotives were left off the passenger train at Wenatchee, and at Skykomish an electric locomotive took the trains between these points over the old route. A 4.5-mile section between Berne and Cascade tunnel was not wired so that the trains with electric engines were taken in each direction over this section by a powerful class 2-8-8-2, four-cylinder Mallet steam locomotive. The freight trains were operated as before until the opening of the new tunnel when the new schedule for electric service went into full effect.

Wenatchee being a division point, all engines and crews both passenger and freight are changed on arrival there. On arrival of all trains at Skykomish from the west, the engine crews shift from the steam locomotives to the electric and continue the trip to Wenatchee. All westbound engine crews similarly transfer from the electric to the steam locomotives and continue to Seattle.

The first ten days of electrical operation over the new route through the new tunnel was without serious incident, but about January 20th the weather began to grow cold and a day or so later the thermometer indicated 15 deg. below zero fahr. on the east side of the mountain and varied between zero and this point for several days and was accompanied by dry snow which drifted badly. On January 22nd the transformer on a locomotive in freight service burned out. This was followed by three other burn-outs of transformers and

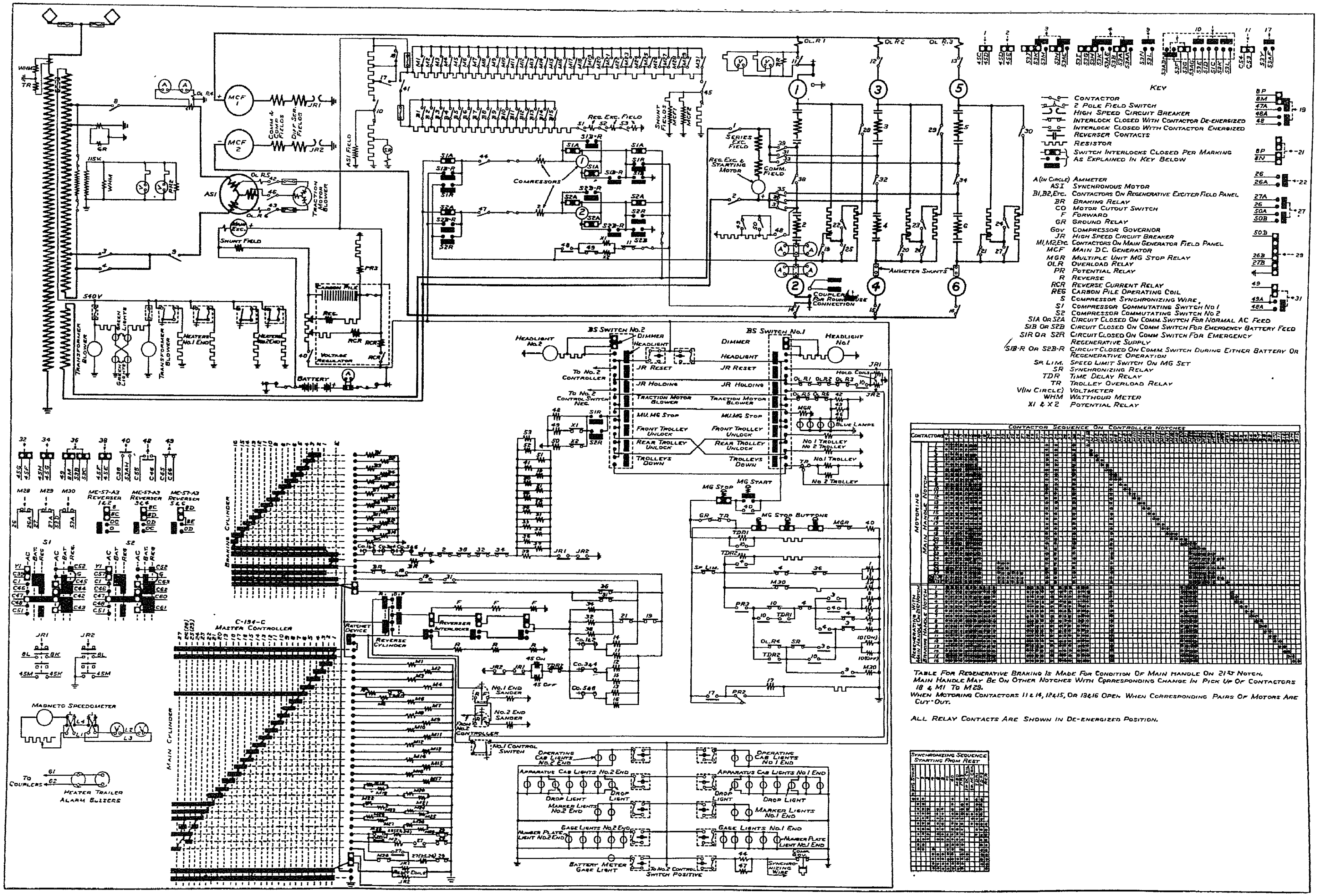
Key
Contactor
2 Pole Field Switch
High Speed Circuit Breaker
Interlock Closed With Contactor De-energized
Interlock Closed With Contactor Energized
Reverser Contacts
Resistor
Switch Interlocks Closed Per Marking As Explained In Key Below
A (In Circle) Ammeter
ASI Synchronous Motor
B1, B2, Etc. Contactors On Regenerative Exciter Field Panel
BR Braking Relay
CO Motor Cutout Switch
F Forward
GR Ground Relay
Gov Compressor Governor
JR High Speed Circuit Breaker
M1, M2, Etc. Contactors On Main Generator Field Panel
MCF Main D.C. Generator
MGR Multiple Unit MG Stop Relay
OLR Overload Relay
PR Potential Relay
R Reverse
RCR Reverse Current Relay
REG Carbon Pile Operating Coil
S Compressor Synchronizing Wire
S1 Compressor Commutating Switch No 1
S2 Compressor Commutating Switch No 2
S1A Or S2A Circuit Closed On Comm. Switch For Normal AC Feed
S1B Or S2B Circuit Closed On Comm Switch For Emergency Battery Feed
S1R Or S2R Circuit Closed On Comm Switch For Emergency Regenerative Supply
S1B-R Or S2B-R Circuit Closed On Comm. Switch During Either Battery Or Regenerative Operation
Sp. Lim. Speed Limit Switch On MG Set
SR Synchronizing Relay
TDR Time Delay Relay
TR Trolley Overload Relay
V (In Circle) Voltmeter
WHM Watthour Meter
X1 & X2 Potential Relay
Contactor Sequence On Controller Notches
Motoring
Main Handle Notch
Regenerating With Main Handle On 21st Notch
Braking Handle Notch
Table For Regenerative Braking Is Made For Condition Of Main Handle On 21st Notch. Main Handle May Be On Other Notches With Corresponding Change In Pick Up Of Contactors 18 & M1 To M29.
When Motoring Contactors 11 & 14, 12 & 15, Or 13 & 16 Open When Corresponding Pairs Of Motors Are Cut-Out.
All Relay Contacts Are Shown In De-energized Position.
Synchronizing Sequence Starting From Rest
BS Switch No. 2
BS Switch No. 1
Headlight No. 2
Headlight No. 1
Dimmer
Headlight
JR Reset
JR Holding
Traction Motor Blower
MU MG Stop
Front Trolley Unlock
Rear Trolley Unlock
Trolleys Down
Blue Lamps
No 1 Trolley
No 2 Trolley
MG Stop
MG Start
MG Stop Buttons
Compressors
Reg. Exc. Field
Series Exc. Field
Reg. Exc. & Starting Motor
Comm. Field
Shunt Fields
Ammeter Shunts
Coupler For Round House Connection
Comm & Comp Fields
Diff Ser Fields
AS1 Field
Traction Motor Blower
Shunt Field
Main Exc.
Carbon Pile
Voltage Regulator
Battery
Transformer Blower
Green Lights
Heaters No. 1 End
Heaters No. 2 End
540V
Braking Cylinder
Main Cylinder
C-194-C Master Controller
Ratchet Device
Reverse Cylinder
Reverser Interlocks
No. 1 End Sander
No. 2 End Sander
No. 1 Control Switch
Operating Cab Lights No. 1 End
Operating Cab Lights No. 2 End
Apparatus Cab Lights No. 1 End
Apparatus Cab Lights No. 2 End
Drop Light
Marker Lights No. 1 End
Marker Lights No. 2 End
Gage Lights No. 1 End
Gage Lights No. 2 End
Number Plate Light No. 1 End
Number Plate Light No. 2 End
Battery Meter Gage Light
To No. 2 Control Switch Positive
Synchronizing Wire
To No. 2 Controller
To No. 2 Control Switch Neg.
MC-57-A3 Reverser 1 & 2
MC-57-A3 Reverser 3 & 4
MC-57-A3 Reverser 5 & 6
Magneto Speedometer
To Couplers
Heater Trailer Alarm Buzzers

FIG. 6—SCHEMATIC WIRING DIAGRAM OF $1-C+C-1$ LOCOMOTIVE

a number of arcovers from terminals of current transformers to ground within less than a week. In every instance, these troubles occurred on a locomotive attached to a freight train westbound through the tunnel. No trouble was experienced on locomotives hauling passenger trains nor on locomotives eastbound hauling freight trains. The loss of four out of a total of 14 main transformers within a week was alarming and seriously threatened the possibility of continuing the handling of all the traffic over the line electrically. On two occasions, before the opening of the new tunnel, there had been instances of arcing to ground from terminals of current transformers which did no serious damage while locomotives were standing inside the new tunnel near the east portal.

A transformer had been lost and an arcover at current transformer terminals on two locomotives had occurred in the old tunnel on one occasion, the first winter after operation began there when the weather was below zero. A frequency changer set used in connection with the work on the new tunnel had burned out and other disturbances on the line had occurred on the same day, so it was thought these troubles were due to surges.

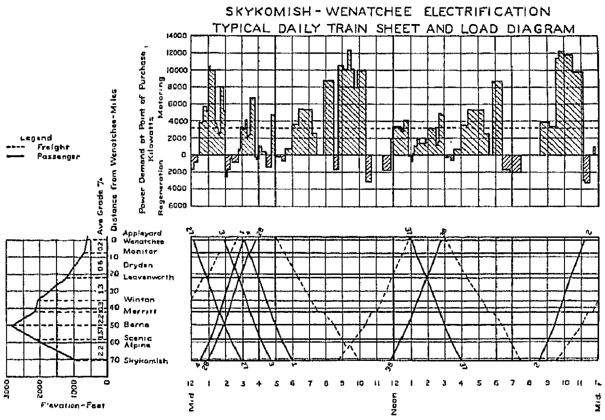

FIG. 7—TYPICAL DAILY TRAIN SHEET AND LOAD DIAGRAM

Additional insulation was installed on the terminals and to the transformers where the trouble seemed to have originated and there had been no further instances of this trouble in the old tunnel. When the arcovers began to occur in the new tunnel, steps were taken immediately to have three surge recorders placed on the trolley circuit, one at each end of the tunnel and one midway between. A fourth recorder was placed on a locomotive running over the entire line. These had just been installed when the sub-zero weather arrived and the more serious troubles began.

It had been noted that when the temperature outside the tunnel was below freezing, there were some signs of condensation on the outside of the locomotive cab and on the inside near the air intakes and that this condensation increased as the temperature outside approached zero. The east end of the new tunnel is at about 634 feet greater elevation than the west end and this, together with the piston action of the moving trains, afforded satisfactory ventilation ordinarily but it was found that the temperature of the air in the tunnel near the middle varied only between 50 and 65 deg. fahr. irrespective of the outside temperature. Since the draft was toward the east portal, the rise in temperature entering the tunnel from that end was much more rapid than from the west end and to add to the difficulties, the outside temperature on the east side of the mountain was usually lower than on the west side.

A locomotive starting out from Wenatchee with normal ventilation, when the outside temperature was below zero, would show little rise in temperature by the time it had reached the east portal of the tunnel so that immediately after entering and encountering the much warmer air, frost began to collect on the outside of the cab and truck and within two or three minutes, the locomotive was thickly coated with frost crystals, the accumulation of which continued until the locomotive began to warm up when this frost would become liquid and begin to drop off. The same action took place inside the locomotive but to a lesser extent.

At times, when the moisture precipitation was greatest, corona conditions were observed to exist on the 11-kv. circuit, particularly at taped joints and terminals. It was no doubt the corona at the surface of the heavily taped terminals connecting the current transformers on the 11-kv. circuit leading to the primary of the locomotive transformer that caused the arcovers to ground at this point.

The surge recorders were left on the circuit from three to four weeks, during which time there were arcovers and burnouts of transformers but a careful examination of all the records failed to indicate that there had been any surges registered, above two times normal. This being well within the limits ordinarily expected from necessary switching operations, surges were eliminated from responsibility for the trouble.

The moisture condition was aggravated by the large volume of air drawn into the locomotive by the blowers for cooling the electrical equipment. The outside temperature east of the tunnel varies from around 100 deg. fahr. in summer to 15 deg. below zero during winter, making it necessary to supply in the hottest weather about 40,000 cu. ft. of air per minute.

Experiences with other locomotives requiring much less ventilating air had indicated conclusively that dangerous quantities of moisture would be carried inside the locomotives by this large volume of air, during rain or snow storms, and in order to protect the electrical equipment from this danger the louvers for the 1—C+C—1 locomotives had been provided at the factory with adjustable shutters by means of which the openings for air intake could be varied from fully open to completely closed.

In order to insure proper ventilation of the apparatus when the louvers were closed, dampers were placed in the outlets for the air from the apparatus, by means of which the air could be directed back into the locomotive for re-circulation through the apparatus, thus replacing the moisture-bearing air from the outside.

While it had not been foreseen that there would be so great a variation between the temperature outside and inside the tunnel as to cause serious trouble, these provisions for closing the louvers and re-circulation of the inside air were readily applicable to the overcoming of this unexpected danger.

By closing the louvers and adjusting the dampers at the beginning of a trip the air inside the locomotive was easily raised to a temperature so nearly approaching that of the air inside the tunnel as to prevent any harmful precipitation of moisture.

When the weather conditions are such as to require the closing of the louvers the temperature outside is never at a maximum so that the re-circulation of the inside air does not cause excessive heating of the apparatus.

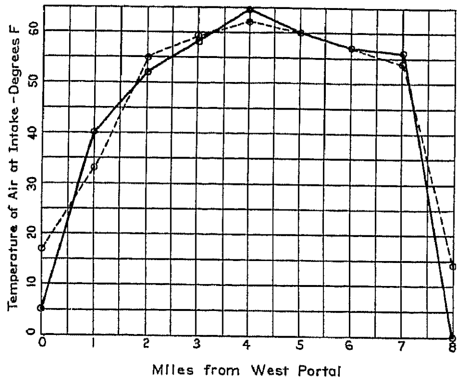

Fig. 8—Diagram Showing Temperature Variations in the New Cascade Tunnel in Near Zero Weather

— West bound trip Jan. 30, 1929
— — — East bound trip Jan. 31, 1929

The electric locomotives have since operated through three winters without any trouble from condensation.

Fig. 8 which shows the variations of the temperature of the air inside the new tunnel would seem to explain why the failures were confined to locomotives on west bound trains since the rate of rise is considerably more rapid when entering from the east portal. The failures were mostly on locomotives attached to freight trains which had taken siding and waited some time before entering the tunnel, thus allowing the apparatus to cool down below normal.

This trouble from condensation is the only serious difficulty that has been experienced in the operation of the electrified line.

The motor-generator type of locomotive is well adapted to the conditions of the service where the freight trains may vary from 2,500 to 5,000 tons trailing and it is desirable to limit the maximum power demand to the most economical point, since the multiplicity of the running speeds makes it practical to select speeds that will keep the power demand at any desired point, with varying train weights on irregular grades.

The first cost of the locomotive and its weight per horsepower is apt to be greater and its overall efficiency somewhat less than other types. The maintenance cost of these locomotives during the three years 1928-9-30 has been 28.66 cents per locomotive mile, or 13.65 cents per 100 tons on drivers.

A comparison of these costs with those of three other electrified roads using locomotives with regenerative braking on heavy grades in similar service is as follows:

| | Locomotive miles | Per locomotive mile | Per 100 tons on drivers |
|---|---|---|---|
| Chicago, Milwaukee, St. P. & P. | 7,939,539 | 14.20c. | 6.92c. |
| Norfolk & Western | 1,520,608 | 46.82 | 17.60 |
| Virginian | 1,562,574 | 48.49 | 12.26 |
| Great Northern | 937,492 | 28.66 | 13.65 |

A direct comparison of operating expenses between steam and electric operation is impossible for the reason that the route now being operated electrically has never been operated by steam and consequently there are no steam records precisely comparable with the electrical records. The shortening of the route and the reduction of the elevation and consequent lessening of the lift by the new tunnel have had an important part in reducing the operating expenses.

However, early in 1920, a study of the old line was made with a view to electrification for the purpose of which operating data and costs were carefully prepared covering 12 months ending September 30, 1919 for the steam operation between Skykomish and Wenatchee through the old tunnel. These data are still available for comparison with corresponding costs covering the year 1929 with electrical operation over the new line. Table I shows a direct comparison of those items of operating expense which are vitally affected by electrical operation for the two years mentioned.

The total cost of the improvements involved in production of the new line and the electrification was in round numbers approximately $25,500,000 made up as follows:

| | |
|---|---|
| 7.9 miles tunnel complete | $14,000,000 |
| 17.0 miles | 5,000,000 |
| 73 miles electrification | 6,500,000 |
| Total | $25,500,000 |

The segregated costs of the electrification were approximately as shown in Table II.

In reviewing the study made in 1920 relative to the electrification of the old line for comparison with the present electrification, it was interesting to find an estimate made at that time of the cost of the proposed electrification of the 80 miles of line between Leavenworth and Gold Bar which was practically the same distance as Wenatchee to Skykomish through the old

TABLE I—COMPARISON OF OPERATING COSTS FOR ITEMS VITALLY AFFECTED BY ELECTRIFICATION

| | Steam | Electric | Difference | |
|---|---|---|---|---|
| | | | Amount | Per cent of steam |
| Route miles | 80 | 73 | 7 | 8.8 |
| Locomotive miles | 767,151 | 406,910 | 360,241 | 47.0 |
| 1,000 ton miles | 485,000 | 408,108 | 76,892 | 15.8 |
| Train miles | 607,000 | 292,930 | 314,070 | 51.7 |
| Costs— | | | | |
| Enginemen | $276,597 | $ 80,049 | $196,548 | 71.0 |
| Trainmen | 175,819 | 77,413 | 98,406 | 56.0 |
| Fuel or power | 659,850 | 269,298 | 390,552 | 59.2 |
| Locomotive repairs | 243,114 | 109,085 | 134,029 | 55.1 |
| Enginehouse | 67,260 | 22,885 | 44,375 | 66.0 |
| Lubricants | 3,325 | 5,525 | +2,200 | 66.2 |
| Supplies | 3,414 | 1,643 | 1,771 | 51.9 |
| Water | 1,308 | | 1,308 | 100.0 |
| Substations | 5,543 | 5,995 | + 452 | 8.2 |
| Distribution | 3,411 | 41,917 | +38,506 | 1128.9 |
| Total | $1,439,641 | $613,810 | $825,831 | 57.3 |
| Average cost per 1,000 ton miles | 2.968 | 1.504 | 1.464 | 49.3 |
| Average cost per train mile | 2.372 | 2.095 | 0.277 | 11.7 |
| Average tons per train freight | 1,882 | 3,021 | 1,139 | 60.5 |
| Average tons per train passenger | 494 | 568 | 74 | 15.0 |
| Average road time freight | 13.4 | 5.5 | 7.9 | 59.0 |
| Average road time passenger | 4.1 | 2.8 | 1.3 | 31.7 |
| Average mi. per hr. freight | 6.0 | 12.9 | 6.9 | 115.0 |
| Average mi. per hr. passenger | 19.4 | 25.5 | 6.1 | 31.4 |

PROPORTIONED BETWEEN FREIGHT AND PASSENGER

| | Steam | | Electric | |
|---|---|---|---|---|
| | Freight | Passenger | Freight | Passenger |
| Locomotive miles | 466,428 | 300,723 | 199,806 | 207,104 |
| Train miles | 207,286 | 399,720 | 98,478 | 194,452 |
| 1,000 ton miles | 390,000 | 95,000 | 297,550 | 110,558 |
| Total cost items affected | $1,067,641 | $372,000 | $391,810 | $222,000 |

tunnel and would require the same electrical equipment. The estimated cost of the complete electrification at that time was $6,463,750 or $80,800, per route mile. Of this amount, $3,250,000 or 50.28 per cent, was for electric locomotives.

The savings from electrical operation estimated for items affected were $639,703. While a considerable portion of the savings shown in the above comparison favorable to electrical operation is due to the new tunnel which shortened the route and decreased the lift, this improvement would not have been practical without the electrical operation of the tunnel. The decision to build the tunnel was reached only after a careful report had been prepared which indicated that interest on the capital charge would easily be covered by the saving in like charges for new snow shed construction and in maintenance charges for same in the future, thus putting the investment for the new tunnel on a self-supporting basis.

The saving in operating expense shown is equal to 12.63 per cent on the gross cost of the electrification which, together with the shortened time and other improvements in the service, makes the electrification a favorable investment with a normal volume of traffic. The electrical equipment is easily capable of handling an increase of 50 per cent in the freight traffic and with such an increase, the saving in operating expenses would be in about the same proportion, making the return on the gross investment for electrification approximately 18 per cent.

TABLE II—COST OF ELECTRIFICATION WENATCHEE TO SKYKOMISH AFTER DEDUCTION OF $174,603.73 CREDIT FOR THE 14 MILES ABANDONED BETWEEN SCENIC AND CASCADE TUNNEL

Route miles 73
Track miles 91

| | Amount | Per route mile | Per cent of total | |
|---|---|---|---|---|
| | | | Less locomotives | Including locomotives |
| Substations, etc. | $1,062,611 | $14,556 | 33.63 | 16.21 |
| Transmission system | 531,967 | 7,287 | 16.70 | 8.12 |
| Power distribution | 368,040 | 5,042 | 11.56 | 5.62 |
| Poles and fixtures | 567,265 | 7,771 | 17.81 | 8.66 |
| Telephone and telegraph changes | 157,440 | 2,157 | 4.94 | 2.40 |
| Signals and interlocks | 155,970 | 2,136 | 4.90 | 2.38 |
| Shops, machinery, tools | 138,357 | 1,895 | 4.34 | 2.11 |
| Engineering | 203,512 | 2,788 | 6.39 | 3.10 |
| Total less locomotives | $3,185,162 | $43,632 | 100.00 | 48.60 |
| Locomotives | $3,368,338 | $46,141 | | 51.40 |
| Total | $6.553,500 | $89,773 | | 100.00 |

The capacity of this portion of the line which, with a congestion of traffic, would, with steam operation, undoubtedly become the bottle neck of the system, has been increased 100 per cent as is indicated by the records. These show that whereas with steam operation in 1920, three steam locomotives averaged approximately six hours to take a 2,250-ton train the 24.3 miles from Skykomish to the old Summit, in 1929, two electric locomotives, averaged about 1½ hours to take a 5,000-ton train the 21.2 miles from Skykomish to the new summit, an increase in schedule speed of from four miles to 14 miles per hour more than double the tons in one-fourth the time on the most difficult grade.

In ton miles per train hour, this is 70,666 for the electric as against 9,112 for steam, a ratio of 7.7 to 1 in favor of electrical operation.

## Discussion

**W. F. Coors:** That part of the paper which gives the details of one of the unexpected electrical troubles encountered in the operation of these locomotives, is of particular appeal from a practical viewpoint. Electric locomotives, technically speaking, are very similar to substations on wheels for the conversion of electrical to mechanical energy. They have transformers or resistors, rotating parts, protective electrical equipment, controlled switching mechanism and some other features which bear similar functionary relation to the apparatus found in any substation used purely for the conversion of electrical energy. However, in addition to having the final output taking the form of mechanical energy, the electric locomotive in heavy trunk line service is exposed in operation to outdoor weather and climatic conditions with changes, dust and dirt, vibrations and road shocks, more infrequent cleanings and inspections; which conditions are not ordinarily met with in stationary work. The Great Northern locomotives with their motor-generator conversion of alternating to direct current for the traction motors, carry out the substation simile to a further degree.

The expected operation of electrical equipment in locomotives or substations is, of course, usually subject to prediction from preliminary tests with mathematical certainty. But on all large projects of this kind there are always, seemingly, certain local conditions which enter in to cause failures when operation is started; and these may have their seat in some one particular feature of design, small of itself apparently, but leading into complications. To solve such difficulties the past experience of the engineer renders itself to an advantage.

On the Milwaukee Road electrification there were several troubles encountered on electrical equipment due to unexpected moisture conditions affecting insulation. One of these was where the depression in the top of the traction motor frame housings for recessing the field pole cap-screw heads, filled with snow in some kinds of weather. The snow would melt later when the traction motors warmed up at work and the resulting water ran through the bolt holes into the traction motor cases. This usually resulted in field coil insulation failures. The application of battery sealing compound filling these recesses, obviated this difficulty.

Another kind of failure was possible because at first the electric locomotives were run into a steam engine house for repair. Coming in from below-zero weather outside, the metal parts would have a thick, white frost congeal on them from the warm, moist air inside the house. Then later, if the locomotive was held inside, this frost would melt slowly, the water dripping from armatures, field coils, and switches for some time during the melting process. If allowed to set for an appreciable period afterward, the insulation resistance of certain parts of the locomotive decreased to the point where failure was probable on the 3,000-d-c trolley current. Other parts where the water drained off freely gave less indication of this possibility. It was feasible to put such a locomotive in service after the frost had first congealed on the parts, before it started melting, in which case the brushes on the commutators sometimes scraped off frost 1/16 in. deep. A few flashovers were caused by this but operation was possible. While in operation, that part of the frost which melted on windings heated by carrying current, was found not to cause serious difficulty because to the heat working outwardly, the motor or such apparatus in service would have also a heavy draft of ventilating air through it, preventing the accumulation of moisture pockets resulting in the saturation of any insulating material.

Another difficulty came from snow being blown into the traction motor housings from the ventilating blower system on a certain type of the locomotives. The intakes of these blowers, while not entirely exposed, were under the cab structure on the trucks; and in weather where light, dry snow was falling, it would be sucked into the ventilating system and deposited on the traction motor armatures. This, in itself, might not have been disastrous but due to the internal ventilating ducts in the armature core structure, this snow would be trapped and melted in pockets with resultant insulation deterioration. These failures usually showed up some time later if the locomotive had been held under conditions for this trapped moisture to melt. Correction of such failures came from changing the ventilation system to what was similarly done later on the Great Northern Railway.

The experience gained from these and other electrifications indicates that certain refinements usually prove necessary after operation has started to take care of unprecedented local conditions. These are determinable mainly from experience in the manner that the automobile has been made so universally adaptable. Electric locomotive designers perhaps can find much of adaptability from the automobile designers; and can neglect much of former steam locomotive practise when it comes to things of purely legendary value. It is prospective that as more electric locomotives are built for more and more electrification work these accidental features of design failure will be worked out to complete elimination.

**R. T. Strong:** In considering any railway electrification, a careful distinction must be made between the terms "locomotive unit" and "locomotive." A locomotive may consist of one, two, three, or perhaps even more locomotive units.

It is assumed that the reader is familiar with the "standard system" of electric locomotive classification here used, in which numerals indicate non-driving axles, and letters indicate driving axles.

It was originally intended by the railway to have two types of locomotives, namely the two unit locomotive originally purchased, type 1 – D – 1 + 1 – D – 1, for freight service, and the single unit locomotive, type 1 – C + C – 1, for passenger service. However, it was soon found in operation that limiting the use of a particular class of locomotive to certain particular service, resulted in unnecessary expense through lost crew time, and dead mileage.

The most economical operation was obtained by using locomotives interchangeably in all types of service. Five different make-ups of locomotives are now in use, as shown by the following tabulation, operation in each case being in multiple, thus requiring only a single crew per locomotive. The flexibility of motive power thus obtained is clearly shown by the following table.

| No. of units per locomotive | Locomotive classification | Loco. weight (tons) | Tractive effort continuous (pounds) |
|---|---|---|---|
| 1....... | 1 – D – 1 | ......184 | ........ 44,250 |
| 1....... | 1 – C + C – 1 | ......269.5 | ........ 60,500 |
| 2....... | 1 – D – 1 + 1 – D – 1 | ......369 | ........ 88,500 |
| 2....... | 1 – C + C – 1 + 1 – C + C – 1 | ......539 | ........121,000 |
| 3....... | 1 – D – 1 + 1 – D – 1 + 1 – D – 1 | .....552 | ........132,750 |

There is some slight discrepancy between the weights given above, and those previously published. The above weights are those of the latest units delivered.

From the above discussion it will be seen that the selection of unit sizes so as to obtain the greatest flexibility combined with the maximum standardization, is of the greatest importance in a new railway electrification. The Pennsylvania Railroad, in its electrification now in progress, has probably gone further than any other railway in this regard.

The flexibility of the single-phase equipment, is well illustrated by the conversion of two 50-ton locomotives and one passenger car from the old Inland Empire System at Spokane, for operation on the Great Northern main line electrification. The only change necessary was the substitution of transformers having an 11,000-volt high tension winding, in addition to the 6,600-volt winding used on the Inland Empire System. For nearly a year, during which time the condensation difficulties described by Mr. Cox occurred, one of these locomotives which was then 23 years old, regularly made two trips per day with a local passenger train over the main line electrification.

The history of most railway electrifications is that the train weights originally specified by the railway have rarely been adhered to. As the railway operating officials observe the ease and economy with which the electrification handles large trains, they keep continually increasing the train sizes. This is well illustrated by the statement in the paper under discussion, that the original three-phase electrification in the old Cascade Tunnel was designed to pull a maximum of 1,600 tons, but actually trains of 2,200 tons were pulled before the tunnel was abandoned. Likewise, the new electrification was first designed for a maximum of 3,500-ton trains, but 5,000-ton trains are now being handled. It was at first thought that the Tumwater Power Plant of 4,000-kw capacity, supplemented by only a small amount of additional power, would be sufficient for the electrification. Actually, the present power supply at Skykomish, Tumwater, and Wenatchee totals 19,000 kw.

The point of this discussion is that the electrical engineer laying out a new railway electrification must keep in mind this tendency, and leave an ample margin in the design for increases in train weight.

Also this tendency introduces a dangerous factor, inasmuch as steam railway operating men are accustomed to loading their steam motive power to its limit. Steam equipment will protect itself by refusing the load before it damages itself. Electric motive power does not thus protect itself, and overload does not show up immediately, but appears at some later time in the form of excessive maintenance cost. Therefore the electrical engineer must carefully watch the operating temperatures of his equipment in a new electrification, to prevent overloading due to this tendency of the operating men to push the equipment to its limit.

In connection with the condensation difficulties described in this paper, there were two conditions contributing to the high temperatures in the tunnel which are not mentioned; first, the presence of warm springs in the tunnel; and second, the heat thrown off by the chemical action of the setting of the newly poured concrete. Colonel F. Mears, Assistant Chief Engineer of the Great Northern Railway, has some very interesting figures on this second condition, showing that newly poured concrete gives off appreciable amounts of heat for a long period of time.

The effect of these two conditions is shown by the fact that one year after the opening of the tunnel, under practically identical weather conditions, the maximum temperature inside the tunnel was only 56 deg F, a drop of 9 degrees from the figure shown by Mr. Cox.

The condensation difficulties were aggravated by the fact that the tunnel air was completely saturated with moisture from the quantities of warm water draining out alongside the track. The eastern end of the tunnel was filled with steam for nearly one mile, and a plume of steam constantly rose from the east portal. The difficulties with the locomotives were entirely due to condensation within the cabs, and not to snow or water drawn in from the outside.

In the case of the 1 – D – 1 locomotive, dampers were installed in the air ducts, with two settings, "summer operation" and "winter operation." In the position marked "summer operation" the air is drawn from the outside, and discharged to the outside of the cab. In the position "winter operation," a large proportion of the air is recirculated within the cabs. It is only necessary to change the position of these dampers twice each year.

These conditions deserve being discussed rather fully, in order that they may be foreseen and provided for by the electrical engineer in future similar projects. It is rather an anomaly, that after designing the ventilation of the cabs with a view primarily to keeping the electrical equipment cool, that it was necessary to change the air circulation so as to keep the equipment warm.

No mention was made in the paper of the catenary system. The Great Northern Railway used the simple inclined catenary similar to that described in Mr. G. I. Wright's paper on the Reading Electrification, as distinguished from the chord catenary used by the Chicago, Milwaukee, St. Paul & Pacific Railway Company. With the inclined catenary the messenger cable is offset from the center of the track on curves, sufficiently so that it acts also as a backbone, thus eliminating most of the pull-offs. The correct position of the trolley wire is obtained by varying the length and angles of the hangers. In the chord catenary the messenger cable is held in the center of the track directly over the trolley wire, by pull-offs and a separate backbone.

A very complete and comprehensive report on the Great Northern electrification will be found in Publication No. 079, "Report of the Committee on Electrification of Steam Railroads," of the National Electric Light Association, September 1930.

**G. H. Walker:** In connection with the paper it may be of interest to outline briefly the electrical system of this electrification. Power is purchased at three-phase 60 cycles at Skykomish and Wenatchee and at 25 cycles single-phase at the Tumwater hydroelectric plant on the Wenatchee river, about twenty-five miles west of Wenatchee, from the Puget Sound Power and Light Company. Frequency changers at Skykomish and Wenatchee convert the three-phase 60-cycle power to single-phase 25-cycle and the three points of power delivery are connected with a double circuit single-phase 44-kv transmission line. The contact system is 11,500 volts single-phase 25 cycles. It is simple catenary construction inclined on curves supported from steel bracket arms on wood poles. This contact system is fed at Skykomish and Wenatchee from the frequency changers stations and from the 44-kv transmission circuits at five intermediate points through stepdown transformers located adjacent to the track.

Power is purchased under a so-called two-part contract, providing for a maximum demand charge plus an energy charge. The demand charge has a primary and secondary rate. The first 5,000 kw are charged for at the primary rate and the next 8,000 kw at the secondary rate. Demand in excess of 13,000 kw is charged for at the primary rate. The maximum demand is determined by the average of the three highest five-minute periods occurring, simultaneously at the three points of delivery, each month.

Because of the increase in demand charge when 13,000-kw demand is exceeded, the railway company finds it advisable to limit the demand to that amount. The method by which the demand is limited may be of interest. Each locomotive unit is equipped with an indicating ammeter on a meter panel visible to the engineman, which is connected in the circuit to the synchronous motor of the motor-generator set. Tests have been conducted to determine the demand for various readings on this ammeter for each type of locomotive unit. The results of these tests have been tabulated in a convenient form and furnished to the train dispatchers. It is the duty then of the train dispatcher in dispatching trains to assign a load limit to each locomotive unit on the line for any given period of time. This he does by orders to the engineman not to exceed so many amperes between certain points or certain times. This system of load limitation has certain serious disadvantages, in that it does not permit a train ascending a grade to take advantage of the reduction in power demand due to another train, descending a grade under regeneration or standing at a station for a meet. However, in the case of the Great Northern Railway, with its relatively short electrification and few number of trains, this method of power limitation has been used without undue handicap to schedules and resulting in a considerable saving in power costs.

Three of the 1 – D – 1 + 1 – D – 1 or Westinghouse locomotives were purchased with standard couplers between the two units. Late in 1929 equipment was purchased and installed in these

TABLE I—POWER CONSUMPTION AND TRAFFIC DATA
GREAT NORTHERN RAILWAY CASCADE ELECTRIFICATION
Year 1931

| | |
|---|---|
| Kwhr purchased | 24,335,844 |
| Kwhr purchased—traction | 23,904,888 |
| Kwhr signals and miscellaneous | 430,904 |
| Kwhr traction—measured on locomotives | 16,528,090 |
| Kwhr hostling and switching—measured at locomotives | 1,797,714 |
| Distribution system efficiency[1] | 69.14% |
| Maximum demand (12,350 monthly average) | 13,107 kw |
| Annual load factor (22.50% avg max. demand) | 21 20% |
| Cost per kwhr purchased power | \$0.009676 |
| Kgtm[2] freight and passenger traffic | 331,907 |
| Kwhr per kgtm[2] freight and passenger traffic purchased | 72.02 |
| Kwhr measured at locomotives freight and passenger traffic | 14,730,376 |
| Kwhr per kgtm[2] freight and passenger traffic—measured at locomotives | 44.38 |
| Kgtm[2] freight traffic | 229,857 |
| Average tons per train freight (3,757 east, 2,994 west) | 3,375 |
| Kwhr measured at locomotives freight traffic | 9,323,020 |
| Kwhr per ktgm freight—measured at locomotives | 40.56 |
| Kgtm[2] passenger traffic | 102,050 |
| Average tons per train passenger (9 cars) | 637 |
| Car miles passenger traffic | 1,457,896 |
| Kwhr measured at locomotives passenger traffic | 5,407,356 |
| Kwhr per kgtm[2] passenger—measured at locomotives | 52.99 |
| Kwhr per passenger car mile—measured at locomotives | 3.71 |
| Locomotive overall efficiency[3] . . . . . Motoring | 65% |
| Regenerating | 60% |

[1] Distribution system is used to transfer surplus power from hydro-electric power station on Railway Co's. system to Power Co's. system. When this function is considered and proportionate losses charged to it the distribution system efficiency becomes 85 per cent.

[2] Thousands of gross ton miles.

[3] Locomotive efficiencies were determined by comparing the measured input to the locomotive with a theoretical output calculated for an average tonnage train run over the profile in each direction.

units to permit operation of one, two or three units as one locomotive. Each unit of this type has the capacity to handle 750 tons on the 2.2 per cent grade or a capacity of 2,250 tons for the three-unit locomotive. This three-unit locomotive has now become practically standard for road freight service. Eastbound out of Skykomish this three-unit road engine with a two-unit helper engine to Merritt will handle 3,750 tons which is the average train. Trains of 4,750 tons have been handled east out of Skykomish with the three-unit 1 – D – 1 road engine, a two-unit 1 – D – 1 and a single unit 1 – C + C – 1 helper engines. The 5,300-ton trains, which are the heaviest handled so far, have used the three-unit road engine and two 1 – D – 1 + 1 – D – 1 helper engines. Westbound this three-unit road engine will handle 3,500 tons from Wenatchee to Merritt without a helper. Schedules are arranged so that eastbound freight trains arrive at Merritt (the foot of the 2.2 per cent grade on the east slope) before the westbound train. Thus the helpers which were cut out of the eastbound train at Merritt are available to help westbound trains up the grade to Berne and continue in the train down to Skykomish.

The 1 – C + C – 1 or General Electric locomotive units also are grouped one, two or three units as a single locomotive for road freight service. A two-unit locomotive of this type will handle 2,000 tons on the 2.2 per cent grade and 3,000 tons on the 1.6 per cent grade westbound. A three-unit locomotive will handle 3,000 tons on the 2.2 per cent grade and 4,500 tons on the 1.6 per cent grade. Eastbound out of Skykomish 4,500-ton trains have been handled by this type three-unit road engine and a 1 – D – 1 + 1 – D – 1 helper engine. Westbound the three-unit 1 – C + C – 1 road engine has handled 4,500 tons from Appleyard to Merritt without a helper. The three 1 – D – 1 unit engine has a continuous output rating of 5,400 hp with a tractive effort of 132,750 lb. The three 1 – C + C – 1 unit engine has a continuous output rating of 9,000 hp and a tractive effort of 181,500 lb.

Table I gives some power consumption and traffic data for the year 1931.

# Theory of the Three-Wire D-C. Generator with Two-Phase Static Balancer

## With Special Reference to Magnetic Phenomena in the Balance Core

BY E. GEOFFREY CULLWICK*
Associate, A.I.E.E.

***Synopsis.***—*When a three-wire d-c. generator with a two-phase static balancer operates with an unbalanced load it is possible that cumulative saturation effects may exist in the balancer core whose magnitude is out of all proportion to the small magnetic unbalance which usually results from the design of the balancer phases. By obtaining an expression for the e.m.f. induced in the balancer winding by the alternating flux the conditions under which these phenomena may be present are studied. It is shown that they are affected by any difference in the resistance of the phases, and that in general their magnitudes vary inversely as the sum of the resistances of the armature winding and the balancer.*

*These conclusions are confirmed by test results and oscillograms taken on an actual machine which show that the maximum flux density in the balancer core may rise to as much as twice the value for which it was designed. The large peaks which occur in the magnetizing current affect the heating of the balancer and also, to a less extent, that of the generator. They also cause considerable pulsations in the terminal voltages of the system.*

### INTRODUCTION

THE exact theory of the three-wire generator with static balancer is not simple, as has been shown by Sengel, Hawkins, and others.† It can be shown that the difference of the voltages on the two sides of the system, when the load is unbalanced, pulsates slightly with double frequency, and Hawkins shows that the out-of-balance current, when entering the balancer coils, does not divide into two equal and unchanging halves (we shall confine our discussion to the two-phase case) but into two portions which pulsate with fundamental frequency but whose mean values are equal.

It is often assumed that the two halves of the balancer winding have exactly equal magnetic effects on the iron core, so that the out-of-balance currents have no direct magnetizing effect. In practise, however, it is extremely difficult, if not impossible, to construct the coils in such a way that their magnetic effects are completely balanced, though any unbalance is usually very small.

It is well known that if an alternating flux is superposed on a direct flux in an iron core the magnetizing current will have dissimilar half-waves, introducing even harmonics (including a constant term) into its analysis. In tests made on a two-phase balancer, in which every effort had been made in its design to balance the two halves of the winding, it was found that even-harmonic peaks occurred in the magnetizing current with an unbalanced load of such a magnitude that they could not be accounted for in a simple manner by the small magnetic unbalance of the phases. Furthermore, it was found that the presence of such peaks was affected by any inequality in the resistances of the two phases of the balancer; with certain conditions of balancer resistance and unbalanced load the peaks were not present at all, and in such cases further increase of unbalanced load resulted in a complete reversal of the phenomena.

The normal magnetizing current of the balancer tested was about 0.25 ampere, while the magnitude of the peaks varied up to over twice the value of the unbalanced direct current, the ratio of peak to unbalanced current decreasing as the latter was increased. Oscillogram No. 7 shows a peak of 58 amperes with an unbalanced current of 63 amperes.

An attempt is made in this paper to give the theory of the two-phase balancer in such a way as to include the explanation of these phenomena.

### THEORY OF THE TWO-PHASE BALANCER

*Mathematical Analysis.* The connections of a two-pole three-wire generator with static balancer are shown in Fig. 1. The balancer is shown external to the machine, being connected to the two diametrical tapping points $C$ and $D$ on the armature winding by means of two slip-rings.

*List of Symbols*

$I_1$ = the load current on the positive side of the system.
$I_2$ = the load current on the negative side.
$(I_1 - I_2)$ = the unbalanced current in the neutral wire.
$R_1$ = the equivalent resistance of the load on the positive side, including the resistance of the leads exterior to the machine and the balancer.
$R_2$ = the equivalent resistance of the load on the negative side.
$R_a$ = armature resistance, measured between brushes.
$R_3$ = resistance of balancer winding and leads between the points $E$ and $C$.

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†See Bibliography.

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$R_4$ = resistance of balancer and leads between $E$ and $D$.
$R_b$ = total resistance of balancer winding and leads, $= R_3 + R_4$.
$L$ = leakage inductance of each parallel path of the armature winding.
$L_1$ = leakage inductance of portion $EC$ of balancer winding.
$L_2$ = leakage inductance of portion $ED$ of balancer winding.
$i_1$ = instantaneous current in balancer winding from $D$ to $C$.
$i_2$ = instantaneous current in portion $CB$ of armature winding.
$e_1$ = instantaneous e.m.f. induced in portions $CB$ and $AD$ of armature winding.
$e_2$ = instantaneous e.m.f. induced in portions $AC$ and $DB$ of armature.
$V_1$ = potential difference across positive lead and neutral.
$V_2$ = potential difference across negative lead and neutral.
$V$ = potential difference across outers of system $= V_1 + V_2$.
$\omega$ = angular velocity of armature.
$t$ = time, starting from the instant when $C$ is at $A$, and again from the instant when $C$ is at $B$.
$q$ = angle $AOC$ divided by $\pi = \dfrac{\omega t}{\pi}$,
$e_3$ = instantaneous e.m.f. induced in each half of balancer winding by the mutual flux. (Each phase is assumed to have the same number of turns.)

The leakage inductances $L$, $L_1$ and $L_2$ are assumed constant, $L$ is assumed to be evenly distributed over the armature.* For the portions $AC$ and $DB$ of the armature we therefore have:

$$\text{resistance} = 2R_a q$$
$$\text{inductance} = Lq$$

and for the sections $CB$ and $AD$:

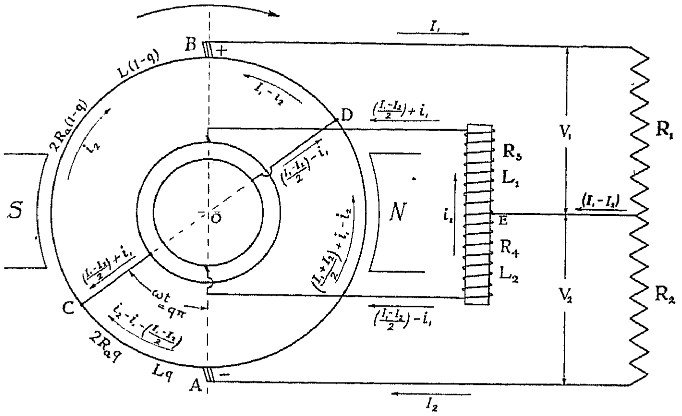
$$\text{resistance } 2R_a(1 - q)$$
$$\text{inductance} = L\,(1 - q)$$

It is clear that in a drum armature the e.m.fs. generated by the field flux in the sections $AC$ and $DB$ must be equal, as are also those generated in $CB$ and $AD$, no matter how the flux may be distorted by armature reaction. Hence the use of the symbols $e_1$ and $e_2$ as above.

The load currents $I_1$ and $I_2$ are assumed to be constant for a steady condition of load. This is not strictly true, but very little error is introduced by neglecting their inductive effects when compared with those of $i_1$ and $i_2$.

The instantaneous currents in the various parts of the circuit will then be as shown in Fig. 1. It is important to notice that the current $i_1$ takes care of any inequality in division of the unbalanced current $(I_1 - I_2)$ in the balancer phases. The total flux set up in the balancer core will be due to the m.m.f. of $i_1$ plus the unbalanced m.m.f. of the currents $\dfrac{(I_1 - I_2)}{2}$ flowing in opposite directions in the two phases.

Since the e.m.fs. generated at any instant in each parallel path of the armature are equal, it follows that the voltage drop in each path, $ACB$ and $ADB$, due to the flow of the armature currents must be the same.



B
+
A
−
C
D
E
O
S
N
$I_1$
$I_2$
$L(1-q)$
$2R_a(1-q)$
$i_2$
$I_1 - i_2$
$\left(\frac{I_1-I_2}{2}\right)+i_1$
$\left(\frac{I_1-I_2}{2}\right)-i_1$
$\left(\frac{I_1+I_2}{2}\right)+i_1-i_2$
$i_2-i_1-\left(\frac{I_1-I_2}{2}\right)$
$\omega t = q\pi$
$2R_a q$
$Lq$
$i_1$
$R_3$
$L_1$
$R_4$
$L_2$
$V_1$
$V_2$
$(I_1-I_2)$
$R_1$
$R_2$

Fig. 1—Connection Diagram of Three-Wire Generator with Two-Phase Static Balancer

The voltage drop in $ACB$ reduces to:

$$2R_a\left[i_2 - q\left(\frac{I_1 - I_2}{2} + i_1\right)\right] + L\left(\frac{di_2}{dt} - q\,\frac{di_1}{dt}\right) \quad (1)$$

and the drop in $ADB$ reduces to:

$$2R_a\left[\frac{I_1 + I_2}{2} + i_1\,(1 - q) - i_2 + q\left(\frac{I_1 - I_2}{2}\right)\right]$$
$$+ L\left[\frac{di_1}{dt}\,(1 - q) - \frac{di_2}{dt}\right] \quad (2)$$

The expressions (1) and (2) must be equal, hence we get:

$$2R_a\left[\frac{(I_1 + I_2)}{2} + q\,(I_1 - I_2) + (i_1 - 2i_2)\right]$$
$$+ L\left(\frac{di_1}{dt} - 2\,\frac{di_2}{dt}\right) = 0 \quad (3)$$

---

*Actually the leakage inductance under the poles will not be the same as that between the poles. If, however, we take this into account by putting the inductances of the sections $AC$ and $DB$ each equal to $L_3$, and those of $CB$ and $AD$ equal to $L_4$, the fundamental equations (**12a**) and (**12b**) are unaltered.

Solving this differential equation in $(i_1 - 2i_2)$ we obtain a steady condition given by:

$$2i_2 = i_1 + \frac{(I_1 + I_2)}{2} + \frac{\omega t}{\pi}(I_1 - I_2) - \frac{\omega L}{2\pi R_a}(I_1 - I_2) \tag{4}$$

Substituting for $i_2$ in the circuits of Fig. 1 gives the equivalent network of Fig. 2. The arrows show the positive directions of the currents and the induced e.m.fs.

The armature currents are:

$$c_1 = \frac{i_1}{2} + \frac{(I_1 + I_2)}{4} + \frac{\omega t}{2\pi}(I_1 - I_2) - \frac{\omega L}{4\pi R_a}(I_1 - I_2)$$

$$c_2 = \frac{3I_1 - I_2}{4} - \frac{i_1}{2} - \frac{\omega t}{2\pi}(I_1 - I_2) + \frac{\omega L}{4\pi R_a}(I_1 - I_2)$$

$$c_3 = \frac{i_1}{2} + \frac{(I_1 + I_2)}{4} - \frac{\omega t}{2\pi}(I_1 - I_2) + \frac{\omega L}{4\pi R_a}(I_1 - I_2)$$

$$c_4 = \frac{3I_2 - I_1}{4} - \frac{i_1}{2} + \frac{\omega t}{2\pi}(I_1 - I_2) - \frac{\omega L}{4\pi R_a}(I_1 - I_2)$$

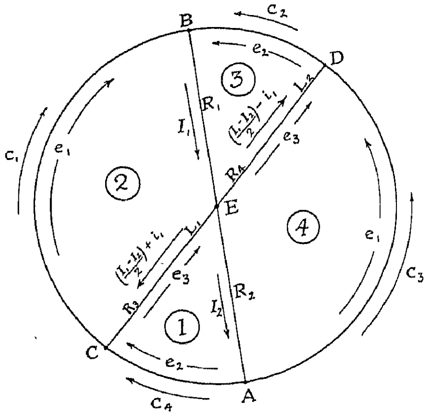


FIG. 2—EQUIVALENT CIRCUIT, AND DISTRIBUTION OF CURRENTS

(For actual values of $c_1$, $c_2$, $c_3$, and $c_4$ see text)

Applying Kirchhoff's second law to the closed circuits (**1**), (**2**), (**3**), and (**4**) of Fig. 2 we obtain the following equations:

$$\begin{aligned} &2R_a \frac{\omega t}{\pi}\left[\frac{3I_2 - I_1}{4} - \frac{i_1}{2} + \frac{\omega t}{2\pi}(I_1 - I_2)\right. \\ &\left. - \frac{\omega L}{4\pi R_a}(I_1 - I_2)\right] - \left[\frac{(I_1 - I_2)}{2} + i_1\right] R_3 \\ &+ I_2R_2 + L\frac{\omega t}{\pi}\left[-\frac{1}{2}\cdot\frac{di_1}{dt}\right. \\ &\left. + \frac{\omega}{2\pi}(I_1 - I_2)\right] - L_1\frac{di_1}{dt} = e_2 + e_3 \end{aligned} \tag{5}$$

$$\begin{aligned} &2R_a\left(1 - \frac{\omega t}{\pi}\right)\left[\frac{i_1}{2} + \frac{(I_1 + I_2)}{4}\right. \\ &\left. + \frac{\omega t}{2\pi}(I_1 - I_2) - \frac{\omega L}{4\pi R_a}(I_1 - I_2)\right] + I_1R_1 \\ &+ \left[\frac{(I_1 - I_2)}{2} + i_1\right] R_3 + L\left(1 - \frac{\omega t}{\pi}\right) \\ &\left[\frac{1}{2}\cdot\frac{di_1}{dt} + \frac{\omega}{2\pi}(I_1 - I_2)\right] + L_1\frac{di_1}{dt} = e_1 - e_3 \end{aligned} \tag{6}$$

$$\begin{aligned} &2R_a\frac{\omega t}{\pi}\left[\frac{3I_1 - I_2}{4} - \frac{i_1}{2} - \frac{\omega t}{2\pi}(I_1 - I_2)\right. \\ &\left. + \frac{\omega L}{4\pi R_a}(I_1 - I_2)\right] + I_1R_1 + \left[\frac{(I_1 - I_2)}{2} - i_1\right] R_4 \\ &+ L\frac{\omega t}{\pi}\left[-\frac{1}{2}\cdot\frac{di_1}{dt} - \frac{\omega}{2\pi}(I_1 - I_2)\right] \\ &- L_2\frac{di_1}{dt} = e_2 + e_3 \end{aligned} \tag{7}$$

$$\begin{aligned} &2R_a\left(1 - \frac{\omega t}{\pi}\right)\left[\frac{i_1}{2} + \frac{I_1 + I_2}{4} - \frac{\omega t}{2\pi}(I_1 - I_2)\right. \\ &\left. + \frac{\omega L}{4\pi R_a}(I_1 - I_2)\right] + I_2R_2 - \left[\frac{(I_1 - I_2)}{2} - i_1\right] R_4 \\ &+ L\left(1 - \frac{\omega t}{\pi}\right)\left[\frac{1}{2}\cdot\frac{di_1}{dt} - \frac{\omega}{2\pi}(I_1 - I_2)\right] \\ &+ L_2\frac{di_1}{dt} = e_1 - e_3 \end{aligned} \tag{8}$$

These four equations also express the fact that the voltage drops in the armature paths *ACB* and *ADB* are equal, which has already been made use of; one of them, therefore, is redundant.

Equating the left-hand sides of equations (**5**) and (**7**) gives:

$$\begin{aligned} (V_2 - V_1) &= (I_2R_2 - I_1R_1) = (I_1 - I_2)\left[\frac{R_b}{2}\right. \\ &\left. + 2R_a\left\{\frac{\omega t}{\pi} - \left(\frac{\omega t}{\pi}\right)^2\right\}\right] + (L_1 - L_2)\frac{di_1}{dt} \\ &+ i_1(R_3 - R_4) \end{aligned} \tag{9}$$

If $L_1 = L_2$ and $R_3 = R_4$ equation (**9**) reduces to the well-known result for the voltage unbalance of a two-phase balancer:

$$\text{Mean value of } (V_2 - V_1) = (I_1 - I_2)\left(\frac{R_b}{2} + \frac{R_a}{3}\right) \tag{10}$$

It should be noted that equation (**9**) is true for both halves of the cycle. In the second-half of the cycle, since $i_1$ is defined as the current in the balancer from $D$ to $C$, the circuits of Fig. 2 hold good if the sign of $i_1$ is reversed and if the time $t$ is measured from the instant when $C$ is at the brush $B$. Also, $R_3$ and $R_4$ must be interchanged, as must $L_1$ and $L_2$, while for continuity of armature e.m.fs. $e_1$ and $e_2$ must replace each other and $e_3$, whose direction is from $C$ to $D$, will reverse its direction relative to the brushes $A$ and $B$. It follows from this that the equation (**9**) is true for both halves of the cycle provided the time $t$ starts from zero whenever the point $C$ passes a brush.

Again, by subtracting equation (**5**) from (**6**), we obtain:

$$\frac{di_1}{dt}\left(\frac{L}{2}+2L_1\right)+i_1\,(R_a+2R_3)$$
$$+R_a\frac{\omega t}{\pi}\,(I_1-3I_2)-2R_a\left(\frac{\omega t}{\pi}\right)^2(I_1-I_2)$$
$$+(I_1-I_2)\,R_3+(I_1R_1-I_2R_2)$$
$$+\frac{(I_1+I_2)}{2}\cdot R_a=e_1-e_2-2e_3 \qquad \textbf{(11)}$$

Substituting for $(I_1R_1-I_2R_2)$ from equation (**9**) we get:

$$2e_3=(e_1-e_2)-\frac{di_1}{dt}\left(\frac{L}{2}+L_1+L_2\right)-i_1(R_a+R_b)$$
$$+R_a(I_1+I_2)\left(\frac{\omega t}{\pi}-\frac{1}{2}\right)+(R_4-R_3)\,\frac{(I_1-I_2)}{2} \qquad \textbf{(12a)}$$

and for the second-half of the cycle ($t$ starting again from zero):

$$2e_3=(e_1-e_2)-\frac{di_1}{dt}\left(\frac{L}{2}+L_1+L_2\right)-i_1(R_a+R_b)$$
$$-R_a(I_1+I_2)\left(\frac{\omega t}{\pi}-\frac{1}{2}\right)+(R_4-R_3)\left(\frac{I_1-I_2}{2}\right) \qquad \textbf{(12b)}$$

It is not possible to determine $i_1$ mathematically, due to the phenomena of saturation and hysteresis in the balancer core; it is in the correct interpretation of the equations (**12a**) and (**12b**), which give the e.m.f. induced in the balancer by the mutual flux, that we shall find the factors which govern the variation of $i_1$.

The fundamental principle which we shall use is that, under steady conditions, the expressions for $2e_3$ as given by the equations (**12**) cannot contain a constant term when all the varying terms are expressed as Fourier series. Since the e.m.f. $2e_3$ is caused solely by a changing flux linking the balancer turns, it follows that every harmonic present in this e.m.f. must be caused by a like harmonic in the mutual flux, and a constant term in the e.m.f. would require for its generation a component of flux which increases continuously at a uniform rate, which is impossible. Hence there cannot be a constant term in the harmonic analysis of the expression for $2e_3$.*

*Effect of Even Harmonics in an Alternating Flux On the Magnetizing Current.* So long as the wave-form of an alternating magnetic flux contains only odd harmonics it follows that the magnetizing current or m.m.f. wave which causes the flux can only contain odd harmonics; as soon, however, as even harmonics (which may include a constant term) appear in the flux wave, greatly magnified even harmonics will be introduced in the magnetizing current wave if the flux density approaches saturation values.

In Fig. 3 is shown the result of a constant term in the flux wave. The flux, when expressed in terms of flux density, has the equation:

$$\Phi = 25 + 80\sin\omega t$$

Consequently the positive peak of the flux wave has a value of 105 while the negative peak only reaches 55. The hysteresis loop for these limits is shown to the left of the figure, and due to saturation it is seen that the positive loop of the flux wave will require a very much larger m.m.f. or magnetizing current than the negative loop. The actual magnetizing current wave is shown at $i$ in the figure, and it is seen to have very large peaks once a cycle. (The actual scale of current is purely relative.)

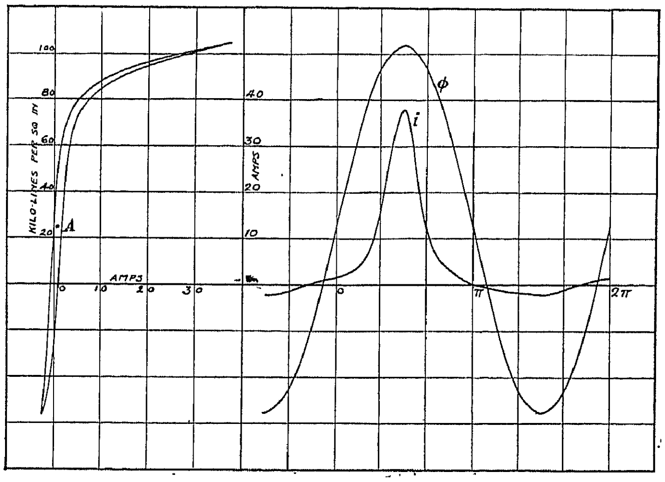


Fig. 3—Wave-Form of Magnetizing Current when the Flux Wave Contains a Constant Term

The harmonic analysis of the current $i$ in Fig. 3, as far as the eighth harmonic, is approximately:

$$i=5.7+1.0\cos\theta+11.8\sin\theta-8.4\cos 2\theta+0.9\sin 2\theta$$
$$-\,5.4\sin 3\theta+3.3\cos 4\theta+2.0\sin 5\theta-1.0\cos 6\theta$$
$$-\,0.54\sin 7\theta+0.4\cos 8\theta \qquad \textbf{(13)}$$

where $\theta=\omega t$

---

*It has been necessary, in developing the equations (**12a**) and (**12b**), to distinguish between the two halves of the cycle and to introduce a discontinuity in the time $t$. It is easily seen, however, that the equations (**12a**) and (**12b**) can be combined into one expression for $2e_3$ in which all the variables are expressed as Fourier series and in which the time $t$ increases uniformly with no discontinuity.

The wave thus contains a large constant term (5.7) and even harmonics, of which the most important is the second. If there were no core loss all the odd harmonics would be pure sine terms, and all the even harmonics would be pure cosine terms.

The magnetizing current wave when a sinusoidal flux (or a flux containing only odd harmonics) is superposed on a direct flux which is maintained by a separate m.m.f. is very nearly the same as that shown in Fig. 3, the only difference being that the origin of the hysteresis loop would be midway between the positive and negative maxima of flux density; *i. e.*, the origin would be at the point *A* in Fig. 3. The magnitude of the current peak would be only slightly less than that shown.

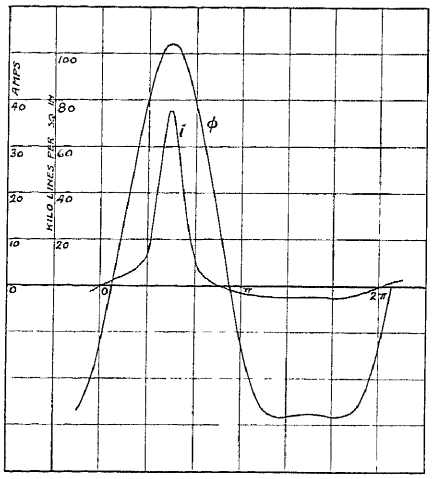


FIG. 4—WAVE-FORM OF MAGNETIZING CURRENT WHEN THE FLUX WAVE CONTAINS A SECOND HARMONIC

Even harmonics in the flux wave, other than a constant term, have the same effect on the magnetizing current provided they are out-of-phase with the odd-harmonic part of the wave. For example, a flux given by:

$$\Phi = 80 \sin \omega t - 25 \sin 2\omega t$$

has equal positive and negative maxima, and consequently no peaks would appear in the magnetizing current, but a flux given by:

$$\Phi = 80 \sin \omega t - 25 \cos 2\omega t$$

has the same positive maximum and nearly the same negative maximum as that shown in Fig. 3, so that the magnetizing current will have the same peak value as before, as is seen in Fig. 4. It will be noticed, however, that the peak is much narrower than in Fig. 3, so that the constant term is less. When analyzed as far as the ninth harmonic, the current *i* in Fig. 4 is given, approximately, by:

$$\begin{aligned} i_1 = 3.02 + 0.86 \cos \theta + 9.16 \sin \theta - 6.8 \cos 2\theta + 0.8 \sin 2\theta \\ - 4.9 \sin 3\theta + 3.85 \cos 4\theta + 3.1 \sin 5\theta - 2.3 \cos 6\theta \\ - 1.62 \sin 3\theta + 1.15 \cos 8\theta + 0.76 \sin 9\theta \end{aligned} \qquad (14)$$

where $\theta = \omega t$

Comparing this expression with (13), we see that the harmonics up to and including the third are greater in (13) than in (14), but that those of a higher order are greater in (14).

It should be noticed that in both expressions the even harmonics (neglecting the sine terms, which are small) are alternatively positive and negative. It is easily seen that if a flux wave contains a positive fourth harmonic, a negative sixth, a positive eighth, etc., in cosine terms, then all these harmonics will add up to increase the positive maximum and decrease the negative maximum of the flux wave and so increase the value of the peak in the magnetizing current.

*Significance of the Equations* (**12a**) *and* (**12b**). Referring now to equations (**12a**) and (**12b**), which together give the instantaneous value of the e.m.f. induced in the balancer winding by the flux which is mutual to both phases at any instant during a complete revolution of the armature of the machine, we have already stated that the expression for this e.m.f., when each term is expressed in the form of a Fourier series, can contain no constant term under steady conditions. Let us now consider each term separately.

1. The term $(e_1 - e_2)$ gives the e.m.f. generated in the machine between the tapping points *C* and *D*. It is an alternating e.m.f., and if the total flux per pole is the same during each half of the revolution of the armature its wave-form will not contain a constant term or even harmonics. We shall see later, however, that $(e_1 - e_2)$ can contain a constant term due to armature reaction.

2. The differential coefficient $\frac{di_1}{dt}$ cannot contain a constant term; since $i_1$ can always be expressed as a Fourier series of a constant term and sine and cosine terms, it follows that its differential coefficients cannot contain any constant term.

3. We have already seen that, under conditions of unequal positive and negative flux maxima, a magnetizing current may contain a constant term. The current $i_1$ is practically equal to the magnetizing current which sets up the flux which induces the e.m.f. $2e_3$, so that we must admit the possibility of a constant term in its analysis.

4. The term

$$R_a (I_1 + I_2) \left( \frac{\omega t}{\pi} - \frac{1}{2} \right)$$

varies over the complete cycle with a triangular wave-form of fundamental frequency, since its sign changes and $t$ starts again from zero at the beginning of the second half-cycle. Its mean value is clearly zero, and its harmonic analysis consists of odd cosine terms only It therefore has no constant term.

5. The term

$$(R_4 - R_3) \frac{(I_1 - I_2)}{2}$$

is itself constant, and depends for its existence on an unbalance of resistance of the two phases of the balancer. It varies directly as the out-of-balance current. It is zero both when the load on the two sides of the system is balanced and also if the two phases have equal resistances.

In general, if any dissymetry in the flux variation introduces a constant term into the current $i_1$, then this constant term can only exist if the other terms of equation (**12**) have constant terms of such a sign and magnitude that the sum of all the constant terms in the expression for $2e_3$ vanishes.

*Effect of Slight Magnetic Unbalance of the Two Phases of the Balancer.* Now suppose that there is a slight magnetic unbalance of the two phases of the balancer in favor of the side *CE* (Figs. 1 and 2). That is to say, if equal currents are flowing in the two halves in opposite directions, there will be a small flux set up in the core in the direction of the m.m.f. of the side *CE*. It follows then, that if the positive side of the three-wire system is the more heavily loaded (as is shown in the diagrams) the components of current $\frac{(I_1 - I_2)}{2}$ in the two phases will set up a small flux in the direction *DC*.

Assuming, to start with, that the alternating flux in the balancer core only contains odd harmonics, it is clear that when this flux is in the direction *DC* the maximum value of the total flux will be greater than its maximum value in the direction *CD*, so that the magnetizing current wave will be distorted in the way shown in Fig. 3, the peaks occuring at the instant of maximum flux in the direction *DC*.

Now let the unbalanced m.m.f. of the two halves of the winding be equal to that produced by a steady current $I_0$, proportional to the out-of-balance current, flowing through the balancer from *D* to *C*, then clearly:

Total flux-producing current

$$= I_0 + i_1 = i_m \qquad (\mathbf{15})$$

and is of the form shown as $i$ in Fig. 3. It is important to notice that, no matter how small the unbalanced effect may be, the true magnetizing current given by (**15**), and hence $i_1$, will have a peak as shown, so long as the magnetization curve begins to bend over at the maximum value of flux density, though of course this peak may be very small.

Let us now study the effect of this slight peak in the magnetizing current on the mutual flux in the balancer core

Let

$$i_m = I_{m0} + I_{m1}(\sin \omega t + \theta_1) - I_{m2}\cos 2\omega t - I_{m3}\sin 3\omega t + I_{m4}\cos 4\omega t + \text{etc.} \qquad (\mathbf{16})$$

then it follows from (**15**) that the current $i_1$ contains the even harmonics $- I_{m2}\cos 2\omega t,\ + I_{m4}\cos 4\omega t$, etc.

The induced voltage $2e_3$ (equations (**12a**) and (**12b**) will therefore contain the even harmonics:

$$-\left(\frac{L}{2} + L_1 + L_2\right) 2\omega I_{m2}\sin 2\omega t + (R_a + R_b)\, I_{m2}\cos 2\omega t + \left(\frac{L}{2} + L_1 + L_2\right) 4\omega I_{m4}\sin 4\omega t - (R_a + R_b)\, I_{m4}\cos 4\omega t - \text{etc.}$$

These are equivalent to:

$$- I_{m2}\sqrt{\{\omega L + 2\omega(L_1 + L_2)\}^2 + (R_a + R_b)^2}\,.\sin\left(2\omega t - \tan^{-1}\frac{R_a + R_b}{\omega L + 2\omega(L_1 + L_2)}\right)$$

$$+ I_{m4}\sqrt{\{2\omega L + 4\omega(L_1 + L_2)\}^2 + (R_a + R_b)^2}\,.\sin\left(4\omega t - \tan^{-1}\frac{R_a + R_b}{2\omega L + 4\omega(L_1 + L_2)}\right) - \text{etc.}$$

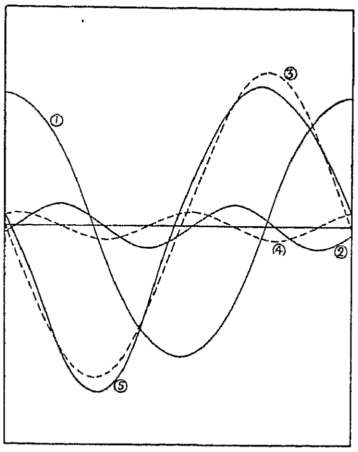


Fig. 5—Showing the Effect on the Flux Wave of Even Harmonics Introduced Into the Induced Voltage Wave by a Distorted Magnetizing Current

The curves show:

(1) That part of the induced e.m.f. $2e_3$ which consists entirely of odd harmonics. For simplicity it is shown as a sine curve

(2) The second harmonic component of $2e_3$

(3) The mutual flux which induces the e.m.f (1)

(4) The mutual flux which induces the e.m f. (2)

(5) The total mutual flux, which has a greater maximum in the direction *DC* than in the direction *CD*

Each of the phase angles in the above expressions is small,* since the leakage reactance $\{\omega L + 2\omega(L_1 + L_2)\}$ is larger than the resistance $(R_a + R_b)$. Now each of the even harmonics in the induced voltage $2e_3$ requires a like harmonic in the mutual flux, leading it by 90 electrical degrees referred to its own frequency, and these even harmonics in the flux combine to increase the flux maximum in the direction *DC* and to decrease it in the direction *CD*. This is shown graphically in Fig. 5, in which the positive direction of all quantities

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*Even if $(R_a + R_b)$ is very large, the phase angles will be less than 90 degrees of the harmonic frequency, and the increase of one of the flux maxima as shown in Fig. 5 will still take place. If $L$, $L_1$ and $L_2$ were all *zero* the phase angles would be 90 degrees, and no cumulative effect would result.

is from $C$ to $D$ in Fig. 2, so that all terms involving a current must be plotted with reversed sign.

The curves of Fig. 5 show:

1. That part of the induced e.m.f., $2e_3$ which consists entirely of odd harmonics. For simplicity it is shown as a sine curve.
2. The second harmonic component of $2e_3$.
3. The mutual flux which induces the e.m.f. (1).
4. The mutual flux which induces the e.m.f. (2).
5. The total mutual flux, which has a greater maximum in the direction $DC$ than in the direction $CD$.

For the sake of simplicity, only the second harmonics in e.m.f. and flux are shown in Fig. 5, but a little thought will show that the effect of all the higher even harmonics is to increase the peak in the flux wave in the direction $DC$.

Since, then, the existence of a small peak in the magnetizing current wave due to slight magnetic unbalance of the phases introduces even harmonics into the flux in such a way as to increase the existing difference between the positive and negative flux maxima, it follows that an additional increase of the magnetizing current peak will take place which will again increase the even flux harmonics. In other words, we have the possibility of a cumulative peaking effect in the current $i_1$; this peak can only attain a permanent steady value if the constant term in the analysis of $i_1$ is cancelled by other consequent constant terms in the remaining terms of equations (**12a**) and (**12b**).

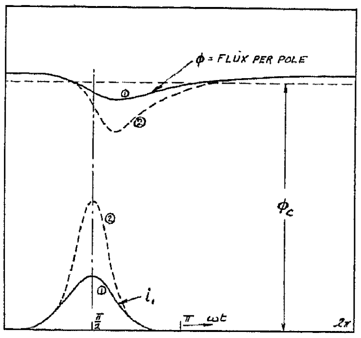


Fig. 6—Showing the Effect of Armature Reaction, When an Unsymmetrical Peak in the Current $i_1$ is Present, on the Total Flux per Pole

*Armature Reaction.* The effects of armature reaction may best be studied by considering the load currents, $I_1$ and $I_2$, and the current $i_1$ separately.

Since the armature has a drum winding the portions $AC$ and $DB$ will not be isolated from each other as is shown in the diagrammatic representation of the armature circuits in Fig. 2, nor will the portions $CB$ and $AD$ be isolated from each other. If we assume that the winding has full-pitch coils the conductors which carry the current $c_4$ in Fig. 2 are situated so that half of them lie in the segment $AC$ and half in the segment $BD$ of the armature surface, and similarly the current $c_2$ flows in conductors which are equally distributed over the same two sections. The magnetomotive forces of the conductors on the armature which actually lie between $A$ and $C$, and between $D$ and $B$, are therefore the same as if these conductors all carried a current equal to $\frac{c_2 + c_4}{2}$, and similarly the m.m.fs. due to the currents $c_1$ and $c_3$ are the same as if all the conductors on the sections $CB$ and $AD$ of the armature carried currents equal to $\frac{c_1 + c_3}{2}$. Now we have:

$$\frac{c_1 + c_3}{2} = \frac{(I_1 + I_2)}{4} + i_1$$

and

$$\frac{c_2 + c_4}{2} = \frac{(I_1 + I_2)}{4} - i_1$$

so that the armature reaction due to the load currents $I_1$ and $I_2$ considered alone is the same as if a current equal to $\frac{I_1 + I_2}{4}$ flowed in each of the parallel paths of the armature. In other words, it is exactly the same as that in a simple d-c. generator with an armature current of $\frac{I_1 + I_2}{2}$ amperes.

The effect of this armature m.m.f. is merely to distort the field flux. Its only results will be to retard the e.m.f. $(e_1 - e_2)$, which will clearly pass through its zero values later if the flux is distorted by the cross-magnetizing effect of the load currents, and also to introduce certain odd harmonics into the wave form of this e.m.f.

Turning now to the armature reaction due to the current $i_1$, which is practically the magnetizing current of the balancer, the general effect is the same as that in a single-phase alternator supplying current to a highly reactive load. The magnetic axis of the armature due to this current is always along the line of the tapping points, and since the maximum value of the current occurs when this axis is practically coincident with that of the poles, it is clear that the conditions are favorable for a maximum reaction on the main flux. From a consideration of the actual direction of the current in the armature, it can be seen that the effect is always demagnetizing except when the tapping points are at the brushes, when the reaction is zero. We thus have a pulsating demagnetizing effect, as in a single-phase alternator as mentioned above.

If $i_1$ were a normal symmetrical magnetizing current in the balancer its armature reaction would be too small to be of any importance, but if it has large peak values once a cycle, due to a cumulative magnetic unbalance, it follows that the demagnetizing effects in the two halves of the cycle will not be the same. Assuming that a peak in $i_1$ takes place in the first half-cycle, the total flux per pole will not be constant but will vary in the manner shown in Fig. 6, (in this sketch the demagnetizing effect in the second half-cycle is neglected, as it is very small). If the variation in flux were exactly proportional at every instant to the demagnetizing m.m.f., the dip in the flux wave would be symmetrical about the ordinate $\frac{\pi}{2}$, but due to hysteresis the change in flux takes place later than the corresponding change in m.m.f., and due to the same cause the flux does not increase to its normal value again until some time after the peak in $i_1$ has disappeared.

This decrease in flux will naturally react on the main field winding, in which e.m.fs. will be induced in such a way as to cause an increase in field current which will follow the variation of $i_1$. For simplicity the field circuit has been omitted from the circuits of Figs. 1 and 2, but actually it forms a coupled circuit with the armature, and the field current divides equally in the two armature paths. Its omission does not introduce any error in the discussion, since the field current is small and has only a very small variation, and further any mutually induced e.m.fs. cannot contain any constant terms since they are always associated with the differential coefficient of a current.

This variation of the total flux per pole is verified by the oscillograms Nos. 13 and 14, which show respectively the e.m.f. induced in a search coil placed round a main pole shoe, and the actual field current of the machine, under conditions where a large peak in $i_1$ was present. It will be noticed in oscillogram No. 13 that the search coil e.m.f. passes through zero later than the instant when the peak is a maximum, and that the generation of the e.m.f. continues some time after the peak has disappeared.

The flux per pole, instead of being given by a constant, must now be expressed by a Fourier series:

$$\text{Flux per pole} = \phi = \phi_c - \phi_1 \sin(\omega t - \psi_1) + \text{higher harmonics} \qquad (17)$$

The general form of equation (**17**) may easily be verified by inspection of the flux curve in Fig. 6. The phase angle $\psi_1$ is less than $\frac{\pi}{2}$.

Now the e.m.f. $(e_1 - e_2)$ generated between the points $C$ and $D$ will be given, very nearly, by:

$$(e_1 - e_2) = K\,\phi \cos \omega t \qquad (18)$$

(neglecting higher harmonics, assumed small, in the periodic factor of $K\phi$).

Substituting for $\phi$ from equation (**17**), we obtain:

$$(e_1 - e_2) = \frac{K\phi_1}{2}\sin\psi_1 + K\phi_c\cos\omega t - \frac{K\phi_1}{2}\sin(2\omega t - \psi_1) + \text{etc.} \qquad (19)$$

The first term of (**19**), it will be noticed, is a constant, which we shall call $E_c$.

The higher harmonics in the expression for $\phi$ in (**17**) do not give rise to any constant terms in $(e_1 - e_2)$; for instance, let there be an $n$th harmonic given by

$$\phi_n \sin(n\omega t - \psi_n)$$

then this introduces a term in the expression for $(e_1 - e_2)$ equal to

$$K\phi_n \sin(n\omega t - \psi_n)\cos\omega t$$

$$= \frac{K\phi_n}{2}[\sin\{(n+1)\,\omega t - \psi_n\} + \sin\{(n-1)\,\omega t - \psi_n\}]$$

and this clearly has a constant term only if $n = 1$.

If any higher harmonics exist in the periodic factor of $K\phi$ in equation (**18**), these will introduce constant terms into $(e_1 - e_2)$ when associated with like harmonics in equation (**17**), but these terms will be small compared with $E_c$, and we may simplify the discussion without introducing any error by neglecting them.

We see, then, that if a peak exists in $i_1$ in the first half-cycle, this will cause a constant term

$$E_c = \frac{K\phi_1}{2}\sin\psi_1$$

in the expression for $(e_1 - e_2)$.

If such a peak exists in the current $i_1$, the Fourier series for $i_1$ will contain a constant term (see equations (**15**) and (**16**)):

$$I_c = I_{m0} - I_0 \qquad (20)$$

The condition for the existence of a steady peak in $i_1$, if $R_3$ is equal to $R_4$, is then:

$$I_c = \frac{E_c}{R_a + R_b} \qquad (21)$$

which satisfies the condition that the expression for $2e_3$, as given by equations (**12a**) and (**12b**), shall contain no constant term.

*Conditions for the Growth of the Peak in the Magnetizing Current.* The conditions under which a cumulative growth of magnetic unbalance may take place can now be formulated. We have already seen that if there is an initial magnetic unbalance in the two phases, however small, this will result in a small peaking effect in the magnetizing current of the balancer which will introduce even harmonics into the wave-form of the mutual flux in such a way as to increase the difference between the positive and negative flux maxima. This will again cause a greater peak in $i_1$, so that the effect tends to be cumulative. It must, however, be governed by the condition that no constant term can exist in the e.m.f. $2e_3$ under steady conditions.

The constant term $E_c$ depends on the existence of a peak in the current $i_1$, so that we may put:

$E_c = f(I_c)$ (*i. e.*, a function of $I_c$) and (**21**) becomes:

$$I_c = \frac{f(I_c)}{R_a + R_b} \qquad (22)$$

Now if the various factors governing (22) are such that, for all values of $I_c$ greater than zero, $I_c$ is greater than $\dfrac{f(I_c)}{R_a + R_b}$, then the only possible steady condition is given by:

$$I_c = 0$$

and the only possible magnetic dissymetry in the core is that which will make $I_{m0} = I_0$ (equation (**20**)).

$I_c$ is in general very small, so under these conditions no appreciable peaking effect can take place.

On the other hand, if the right-hand term of (22) is the greater for small values of $I_c$, the latter will increase in an attempt to satisfy the condition of this equation, so that the cumulative peaking of $i_1$ will take place.

Before proceeding further, it may be helpful to consider the analogous case of the building up of voltage in a d-c. shunt generator, in which an initial residual voltage causes a small field current which in turn produces more voltage, and so on, the growth being limited by the fact that the field current and the terminal voltage are bound together by a double relation; first that the field current multiplied by the field resistance must be equal to the voltage, and secondly that the field current and the voltage are relatively fixed by the magnetization curve of the machine. In order that the voltage may grow, that produced by a certain field current must be more than that required to send that current through the resistance of the field winding, and as soon as these two voltages become equal a stable value is obtained. This is shown graphically in Fig. 7, where the line $R$ gives the relation between volts and field current as required by the field resistance, and $M$ is the magnetization curve of the machine (corrected for the small armature drop due to the field current). The voltage given by the magnetization curve $M$ tends to cause field current, while the potential difference across the field, given by $R$, tends to resist the flow of field current, and for an initial growth of field current the "causing voltage" must be greater than the "resisting voltage."

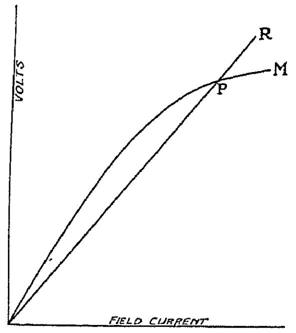


FIG. 7—ILLUSTRATING THE PHENOMENON OF THE BUILDING UP OF VOLTAGE IN A SHUNT GENERATOR

Further, if the effect is to stop at some stable value, then the ratio $\dfrac{\text{causing volts}}{\text{resisting volts}}$ must decrease as the field current increases until it reaches unity, at which point a balance will be obtained and a steady field current and voltage will result. This stable value is shown at the point $P$, where the two curves cross.

It is interesting to note that if the natural laws of magnetic induction were such that the curve $M$ curved the other way the effect would be unstable and the generated voltage would tend to increase indefinitely.

In the case under consideration the "peak value of $i_1$" is analogous to the field current, and the "constant terms" take the place of the voltages in the above discussion. The "causing" constant term is that in $(e_1 - e_2)$, while the "resisting" constant term is that in $i_1$. It will therefore be necessary to determine the relations between the peak value in $i_1$ and the two constant terms which it introduces.

### *Definition of "peak value of $i_1$"*

The term "peak value" as used in the following is taken to be the *difference* of the positive and negative maxima of the current. That is to say, if the magnetizing current is normal and has equal positive and negative maxima, the "peak value" is zero. This is consistent with the fact that such a current would have no constant term in its analysis, and would not cause any constant term in $(e_1 - e_2)$.

For large peak values the smaller maximum value is almost negligible when compared with the greater, but when considering the initial stages of the growth it is important to keep the above definition in mind.

If now a number of curves such as that of $i$ in Fig. 4 be plotted for different values of the second harmonic in the flux wave, making use of the magnetization curve of the sheet steel of which the core is built up, for each curve we obtain a definite peak value and a definite constant term. The current wave so plotted is true magnetizing current, so that the constant term is that given by $I_{m0}$ in equation (**16**). Actually, of course, higher even harmonics are present in the flux waves, but the general form of the variation may be deduced as above. If we plot the values of the constant term on a base of "peak value," we obtain a curve, which is practically linear, shown as $I_{m0}$ in Fig. 8.

The accurate relationship between the constant term $E_c$ and the peak value of the current is more difficult to obtain, but the general shape of the curve may be deduced. We see from equation (**19**) that $E_c$ depends both on the amplitude $\phi_1$ of the fundamental component of the flux per pole and on the magnitude of the phase angle $\psi_1$. As the peak value of the magnetizing current increases, the peak itself becomes sharper and requires a relatively smaller fundamental and relatively larger higher harmonics in its analysis. This effect is transmitted to the time variation of the flux per pole, as is shown in Fig. 6 where the curves (2) show the sharper peaking produced by a higher peak value of $i_1$. It is evident then that the ratio

$$\frac{\phi_1}{\text{Peak value of } i_1}$$

will decrease as the peak value of $i_1$ increases. The phase angle $\psi_1$ will not undergo any appreciable change, so that it follows that the ratio

$$\frac{E_c}{\text{Peak value of } i_1}$$

will also decrease as the peak increases. At the same time, however, it should be noticed that, as the peak increases, the actual peak decrease in flux is apt to increase slightly more rapidly, due to the fact that a steeper part of the saturation curve of the magnetic circuit of the machine is reached. The curve of $\dfrac{E_c}{R_a + R_b}$ in Fig. 8 therefore bends over more rapidly at first, straightening out slightly as the peak value increases.

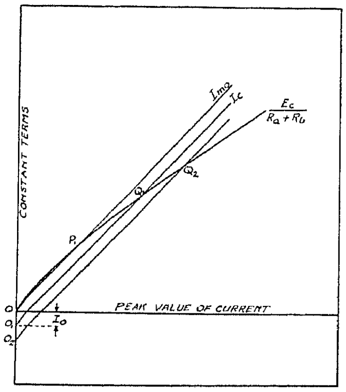


FIG. 8—ILLUSTRATING THE CONDITIONS FOR THE GROWTH OF THE PEAK IN THE CURRENT $i_1$

The curves $I_{m0}$ and $\dfrac{E_c}{R_a + R_b}$ of Fig. 8 together give the possibility of a magnetic unbalance with no out-of-balance current at all. The point $P_1$ where they cross gives the stable value of magnetizing current peak under these conditions. (See oscillogram No. 1.)

When an out-of-balance current $(I_1 - I_2)$ flows, the constant term which must be plotted in Fig. 8 for the current is $I_c = I_{m0} - I_0$ (equation (20)), where $I_0$ is proportional to $(I_1 - I_2)$.

To obtain the conditions for a particular value of $(I_1 - I_2)$, $OO_1$ is set off, as shown in Fig. 8, equal to $I_0$, and the curve $I_c$ is drawn parallel to the curve $I_{m0}$ with the point $O_1$ as origin. The point of intersection $Q_1$ of this curve and that of $\dfrac{E_c}{R_a + R_b}$ gives the final steady value of the peak current.

If a series of such curves be drawn, $O_2Q_2$ etc., the points $Q_1$, $Q_2$, etc., will give the steady peak values corresponding to out-of-balance currents proportional to $OO_1$, $OO_2$, etc., and it is seen from the general shape of the curves that the peak value increases less rapidly than the out-of-balance current.

It is also clear from Fig. 8 that if $(R_a + R_b)$ is increased the result will be a decrease in peak value for any one value of out-of-balance current, and conversely, if $(R_a + R_b)$ is decreased the peak values will be larger than before. (See oscillograms Nos. 15 and 16.)

*Effect of Unbalanced Resistance of the Balancer Phases.* If, in Fig. 2, $R_4$ is greater than $R_3$, it follows from equations (**12a**) and (**12b**) that the current $i_1$ must be such as to contain a constant term which will cancel the term so introduced in addition to $E_c$. Its value, instead of being given by equation (**21**), will now be governed by:

$$I_c = I_{m0} - I_0 = \frac{E_c}{R_a + R_b} + \frac{R_4 - R_3}{R_a + R_b} \cdot \frac{(I_1 - I_2)}{2} \tag{22}$$

so that the peak value of $i_1$ will be greater than before.

On the other hand, if $R_4$ is less than $R_3$, it is evident that the constant term in $i_1$, and consequently the peak value, will be less than when the resistances are balanced. Further, the unbalance of resistance may introduce such a large negative term in equation (22) that the current $i_1$ will have to develop a constant term of opposite sign to that originally present, resulting in a complete reversal of the peak, which will appear in the opposite direction and during the second half of the cycle. (That this is possible may be seen from Fig. 4; a flux given by $\phi = 80 \sin \omega t + 25 \cos 2\omega t$ would have a negative maximum greater than its positive maximum, and consequently the peak in the magnetizing current would be negative and in the second half of the cycle.)

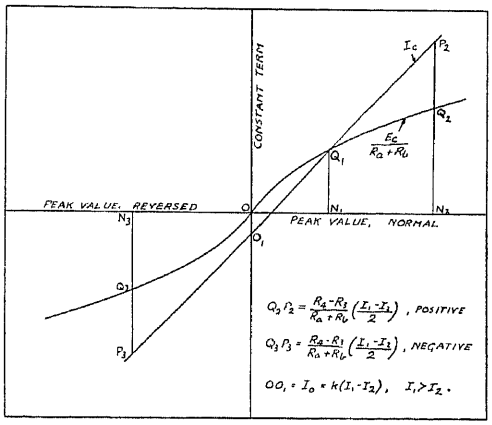


FIG. 8A—ILLUSTRATING THE EFFECT OF UNBALANCED PHASE RESISTANCE ON THE PEAK IN THE CURRENT $i_1$

This effect is shown graphically in Fig. 8A, for a given value of out-of-balance current $(I_1 - I_2)$. The curves of $I_c$ and $\dfrac{E_c}{R_a + R_b}$ are continued back into the negative quadrant as shown, for if the peak reverses it is clear that these constant terms must reverse as well. It should be noticed that the curve of $I_c$, when reversed, starts as before at the point $O_1$, since $OO_1$ is equal to $(I_1 - I_2)$ multiplied by some constant and only reverses if the unbalanced current reverses. In other words, for the condition of a reversed peak we have:

$$-I_c = -I_{m0} - I_0$$

The normal peak value, when $R_3$ and $R_4$ are equal, is equal to $ON_1$, corresponding to the point $Q_1$. If, however, $R_4$ is greater than $R_3$, the peak will be equal to $ON_2$, corresponding to the points $P_2$ and $Q_2$ where $Q_2P_2$ is equal to

$$\frac{R_4 - R_3}{R_a + R_b}\,\frac{(I_1 - I_2)}{2}\,.$$

This clearly satisfies the equation (22).

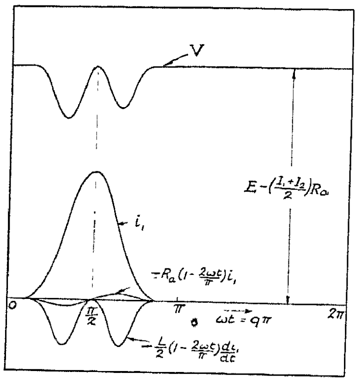


FIG. 9—PULSATIONS IN THE TERMINAL VOLTAGE OF THE MACHINE DUE TO A PEAK IN THE CURRENT $i_1$ OCCURRING WHEN $q = \frac{1}{2}$

If $R_3$ is greater than $R_4$ it follows that $I_c$ must be algebraically less than $\frac{E_c}{R_a + R_b}$; for small values of resistance, or load unbalance, the peak value will now be given by some point in between the points $O$ and $Q_1$, but if the difference in the resistances, or the load unbalance, is large, balance can only be obtained if both the peak and the constant terms $I_c$ and $\frac{E_c}{R_a + R_b}$ reverse. This condition is given by the points $Q_3$ and $P_3$, where $Q_3P_3$ is equal to

$$\frac{R_4 - R_3}{R_a + R_b}\,\frac{(I_1 - I_2)}{2}$$

which is now negative. The peak value is equal to $ON_3$, which is also negative, but numerically less than $ON_2$.

The actual existence of reversed peaks due to resistance unbalance is seen in oscillograms Nos. 4, 9, and 10.

*Effect When the Negative Side of the System Has the Heavier Load.* In the whole of the above discussion it has been assumed that the positive side of the system is the more heavily loaded. If $I_2$ is greater than $I_1$ the actual direction of the out-of-balance current will be towards the center of the balancer, instead of outwards from it, and the initial magnetic unbalance will set up a small flux in the direction $CD$ (Fig. 2); this will start a peak in the magnetizing current in the second half of the cycle instead of in the first, and this peak will introduce even harmonics into the balancer flux which will produce further peaking of $i_1$. Otherwise the effect will be exactly the same as when the positive side was the more heavily loaded.

It follows, since the sign of the peak is opposite to that in the first case, that the signs of the constant terms $(I_{m0} - I_0)$ and $E_c$ will also be reversed, and since the sign of $(I_1 - I_2)$ is reversed the equation (22) still holds. If, therefore, in Fig. 2 the resistance $R_4$ is greater than $R_3$, the peak will never disappear and change sign as the out-of-balance current is increased, no matter which side is more heavily loaded, while if $R_3$ is greater than $R_4$ the reversal is equally likely to occur whether the positive or negative side of the system has the heavier load.

It is important to note that the resistances $R_3$ and $R_4$ in Fig. 2 refer to those sides of the balancer which are connected to the armature taps $C$ and $D$ respectively, and not to the two sides of the balancer as considered apart from the machine.

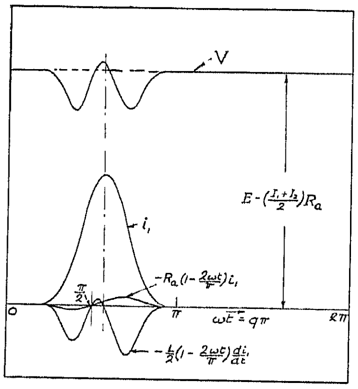


FIG. 10—PULSATIONS IN THE TERMINAL VOLTAGE OF THE MACHINE DUE TO A PEAK IN THE CURRENT $i_1$ OCCURRING WHEN $q$ IS SLIGHTLY GREATER THAN $\frac{1}{2}$

*Pulsations in the Terminal Voltage.* The voltage drop between the brushes $A$ and $B$ due to the flow of the armature current is given by equation (1). If we substitute in this expression the value of $i_2$ as given by equaton (4) we obtain:

Drop due to armature currents =

$$D_{ab} = \frac{(I_1 + I_2)}{2}\cdot R_a + \left(R_a i_1 + \frac{L}{2}\,\frac{di_1}{dt}\right)\left(1 - \frac{2\omega t}{\pi}\right)$$

The terminal voltage $V$ $(= V_1 + V_2)$ is therefore $= E - D_{ab}$, where $E = e_1 + e_2$, the voltage generated in the armature between the brushes.

If we assume that $E$ is approximately constant (actually it decreases slightly due to armature reaction when a peak in $i_1$ occurs) the wave form of $V$ will be given by the curves in Figs. 9 and 10, for the case when a peak in $i_1$ occurs in the first half cycle. Fig. 9 assumes that the peak occurs when $q = \frac{1}{2}$, but when the machine is loaded the instant when $(e_1 - e_2)$ is zero is later than $q = \frac{1}{2}$ due to the distorting of the field by the cross m.m.f. of the armature. Consequently the peak in $i_1$ will occur a little later than $q = \frac{1}{2}$, with the result shown in Fig. 10, where it is seen that the value of $V$ actually rises above its normal value at one point.

In these two diagrams the effects of $i_1$ during the parts of the cycle when it has a normal value are neglected in comparison with the effects of its peak. It should be noted that while the time-base of these diagrams, $\omega t$, is continuous, the relation $\omega t = q\pi$ is only true if $t$ starts from zero at the beginning of each half cycle, since $q$ is never greater than unity.

By combining the above expression for $(V_1 + V_2)$ with equation (**9**), it can easily be shown that both $V_1$ and $V_2$ will have pulsations similar in form to those shown in Fig. 10. Actual oscillograms of these voltages are shown in oscillograms Nos. 6, 7, and 12.

## TEST RESULTS

The machine tested was a 6-pole, 75-kw., 1,200-r.p.m., 125-250-volt, three-wire generator with a full-load current of 300 amperes. The static balancer was of the two-phase type, mounted externally to the machine. It was rated for a maximum out-of-balance current of 75 amperes. The armature resistance of the machine, $R_a$, was approximately 0.015 ohm, while that of the balancer, $R_b$, was approximately 0.065 ohm. These do not include the equivalent resistances of the various brush contacts, which introduce considerable variation into the values of resistance as used in the discussion of the phenomena. For this reason accurate quantitative tests were not attempted, the sole purpose being to examine experimentally the general analytical conclusions of the paper.

It was found that very large peaks occurred in the balancer phase currents when the machine supplied unbalanced loads, and it was further found that these peaks depended only on the unbalanced load and were independent, excepting for the effects of the cross m.m.f. of the armature, of the balanced load on the machine. The generator was compound-wound, but the phenomena were found to be independent of the use of the series winding.

The insertion of the oscillograph shunt in the balancer leads introduced an unbalance in the resistance of the two phases of the balancer, with the interesting results shown in the oscillograms. These are consistent with the previous theoretical discussion, as are the pulsations in the terminal voltages of the system.

The machine was driven by a 6-pole synchronous motor at 60 cycles, this a-c. supply being also used to drive the small synchronous motor which actuated the oscillating mirror for the "time base" on the oscillograph. When the waves were watched on the viewing-screen it was found that several seconds elapsed before the peaks became steady after a change of load. Indeed, when the load was instantaneously changed from a positive to a negative unbalance or *vice versa*, the previous peak persisted for a few moments before reversing and taking up its new steady value. This bears out the cumulative nature of the phenomena, and their dependence on the flux-waves in the balancer core. These flux-waves, containing strong even harmonics, give the effect of direct magnetization, which cannot reverse instantaneously.

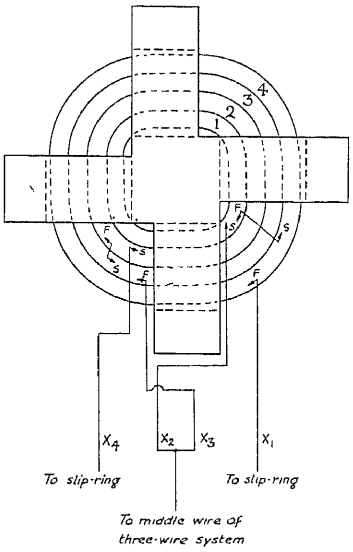


FIG. 11—CONNECTION DIAGRAM AND ARRANGEMENT OF CORE AND COILS OF THE TWO-PHASE STATIC BALANCER

It was also found that the ordinary magnetizing current, with no unbalanced load, showed evidence of unsymmetrical flux variation (see oscillogram No. 1).

*Magnetic Unbalance of Balancer Phases.* The two-phase static balancer has its coils wound concentrically on the center leg of a five-leg G. E. distribution transformer core. The winding is in the form of four coils of two layers each, as in Fig. 11. The coils 1 and 4 comprise one phase, while coils 2 and 3 comprise the other. The exact calculation of the magnetic field set up across the area of the inner leg by equal currents flowing in the two phases in opposite directions is a matter of some difficulty, and is not attempted here. If the coils are equally spaced it will not, however, be zero, as may easily be seen if the magnetic field be calculated at the center of four equally spaced concentric short solenoids, in which the current is the same in each coil and in such a direction that the inner and outer coils oppose the two center ones.

The actual windings of the balancer tested may be represented approximately by four concentric solenoids of circular section 4.875 in. long and with radii equal to 2.201 in., 2.534 in., 2.866 in., and 3.199 in., each having 34 turns. If a current $I$ amperes flows through each coil in such a way that the outer and inner oppose the magnetic action of the two central ones, the magnetic field at the central point of the arrangement will be equal to:

$$H_c = 0.0244\, I \text{ oersteds}$$

(If they all magnetized in the same direction the field at the center would be about 23.6 $I$ oersteds). The direction of this small field is the same as that set up by the outer and inner coils alone.

The actual existence of an unbalance in the magnetic effect of the phases on the core was tested as follows. The leads $X_1$ and $X_3$ (see Fig. 11) were connected together and the leads $X_2$ and $X_4$ were connected through a rheostat, circuit breaker, and ammeter to a source of direct current. Any current allowed to flow in this arrangement will flow through the two phases in such a direction that they would oppose each other magnetically. Search coils of the same number of turns were wound in the same direction round each of the four outer legs and connected in series to a ballistic galvanometer. Direct currents varying up to about 60 amperes flowing in the coil were broken by opening the circuit breaker, the result of the test showing that the flux set up by a current of $I$ amperes was approximately equal to 10 $I$ maxwells.

This result gives a figure which is too low on account of the fact that the current was broken but not reversed, so that there was a possibility of some residual magnetism. The galvanometer flings were, however, exactly proportional to the current broken, over the range of the tests. Further, the flux measured was the total flux in the four outer legs, which is less than that in the center leg due to leakage.

In interpreting the above result, it should be remembered that the permeability of the core with such a weak magnetizing force would be very low, possibly of the order of 50. The test showed quite definitely that a magnetic unbalance of the phases did exist, and the analytical discussion of the phenomena only presupposes a small unbalance. Theoretically any unbalance, however small, would be sufficient to start the cumulative growth of the peaks in the magnetizing current, provided the normal maximum flux density in the core lies on a part of the magnetization curve which is only slightly curved towards the saturation region. The maximum flux density in the center leg of the balancer tested, under conditions of symmetrical flux-variation was 70.4 kilolines per square inch, at which point the magnetization curve is by no means straight.

## OSCILLOGRAMS

In order to study the wave form of $i_1$ the oscillograph shunt was inserted in one or other of the leads between the slip-rings and the balancer. The lead to the slip-ring nearer to the commutator will be called "lead $A$," while the lead to the slip-ring nearer to the end of the shaft will be called "lead $B$."

The wave-forms thus obtained are those of the currents

$$\frac{I_1 - I_2}{2} + i_1 \text{ and } \frac{I_1 - I_2}{2} - i_1$$

(see Fig. 1).

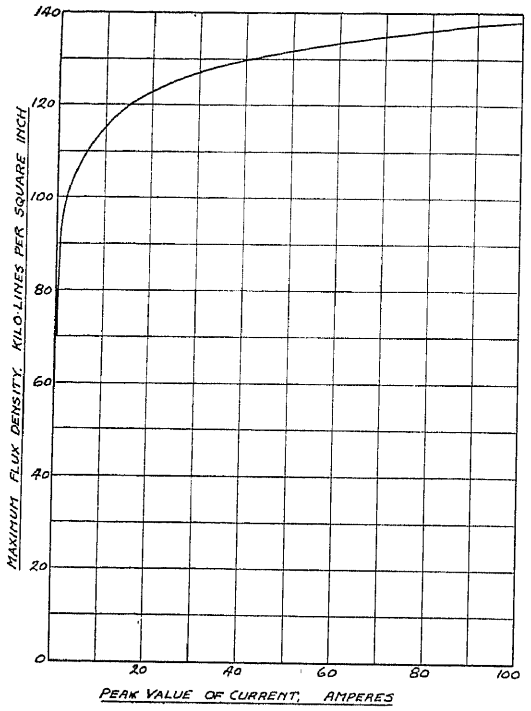


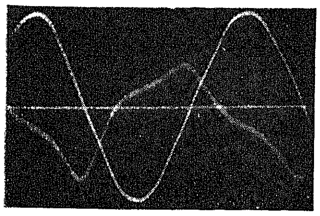
FIG. 12—RELATION BETWEEN VALUE OF PEAK IN THE CURRENT $i_1$ AND THE MAXIMUM FLUX DENSITY IN THE CORE OF THE BALANCER

The first half of the cycle as understood in the discussion appears as the second half in the oscillograms. The choice of which shall be considered as the first half of the cycle is entirely arbitrary and there is no inconsistency in the results.

It was found that, when the oscillograph shunt was in the lead $A$, the peak reversed at some value, positive or negative, of $(I_1 - I_2)$, but when the shunt was placed in the lead $B$ no reversal ever took place.

## CONCLUSION

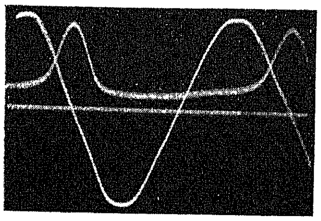
The most important fact which comes to light in these results is that, although the balancer windings are designed to give very nearly perfect magnetic balance of the phases, saturation phenomena in such a machine may grow to proportions immensely greater than would at first sight be expected. The large magnetizing current peaks give evidence of very high values of maximum



No. 1—No Unbalanced Load, and Mid-Point of Balancer Disconnected from Three-Wire System

Shows magnetizing current in the balancer, and the voltage across the slip-rings

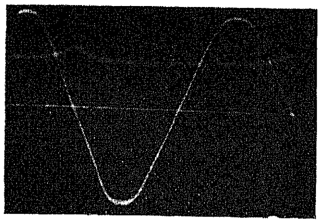
R.m.s. value of current = 0.25 amperes approximately



No. 2—4 Amperes Unbalance, Negative Side, 250 Volts D.C.

Shows current in lead *A* and voltage across slip-rings

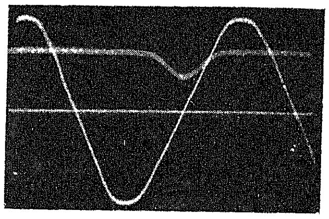
Peak value of current $i_1$ is 6.25 amperes. This is less than normal due to resistance of oscillograph shunt (0.102 ohms) introduced into the balancer circuit



No. 3—37 Amperes Unbalance, Negative Side, 205 Volts D.C.

Shows current in lead *A* and voltage across slip-rings

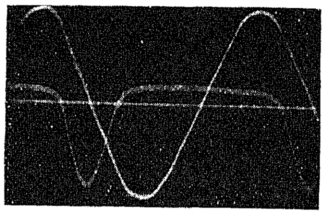
Peak value of $i_1$ is 4.1 amperes, very much reduced by resistance of shunt (0.026 ohms) producing an unbalance of resistance in the balancer phases



No. 4—47.5 Amperes Unbalance, Negative Side, 250 Volts D.C.

Shows current in lead *A* and voltage across slip-rings

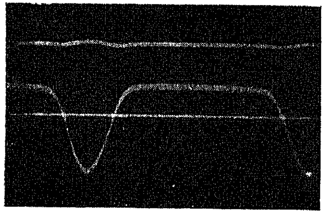
Peak value of $i_1$ is 9.5 amperes, completely reversed due to unbalance of resistances of balancer phases, due to oscillograph shunt (0.026 ohms)



No. 5—4 Amperes Unbalance, Negative Side, 250 Volts D.C.

Shows current in lead *B* and voltage across slip-rings

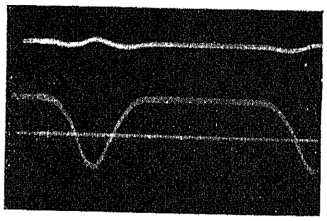
Peak value of $i_1$ is 11.6 amperes, increased due to oscillograph shunt resistance (0.012 ohms) in lead *B*



No. 6—18.2 Amperes Unbalance, Negative Side, 250 Volts D.C.

Shows current in lead *B* and voltage across the loaded side of the system

Peak value of $i_1$, is 27.0 amperes, resistance of the oscillograph shunt 0.026 ohms

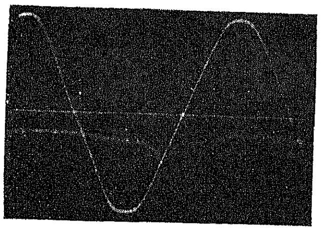


No. 7—63 Amperes Unbalance, Negative Side, 250 Volts D.C.

Shows current in lead *B* and volts across the outside wires of the system

Peak value of $i_1$ is 58 amperes, resistance of shunt 0.0112 ohms

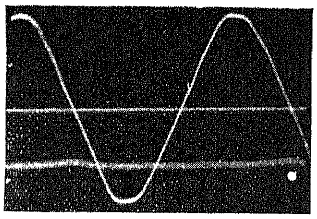
D-c. voltage shows a total variation of 18.5 volts, or 7.4 per cent



No. 8—3.9 Amperes Unbalance, Positive Side, 250 Volts D.C.

Shows current in lead *A* and voltage across slip-rings

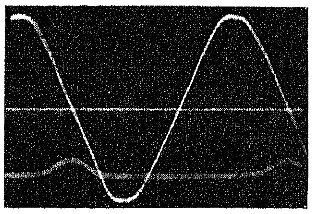
Peak value of $i_1$ is 4.0 amperes. Resistance of shunt 0.102 ohms



No. 9—48.9 Amperes Unbalance, Positive Side, 250 Volts D.C.

Shows current in lead *A* and voltage across slip-rings

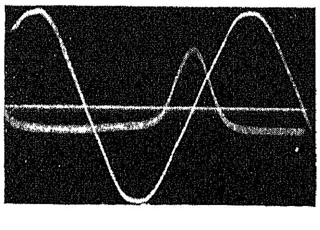
Peak value of $i_1$, is very small, having just reversed. Resistance of shunt 0.026 ohms



No. 10—59.5 Amperes Unbalance, Positve Side, 250 Volts D.C.

Shows current in lead *A* and voltage across slip-rings

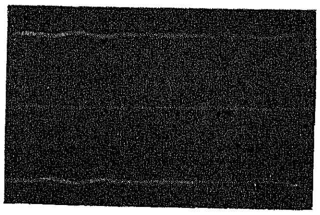
Peak value of $i_1$, is 7.4 amperes, having completely reversed due to shunt resistance, 0.026 ohms, in lead *A*



No. 11—4.0 Amperes Unbalance, Positive, 250 Volts D.C.

Shows current in lead *B* and volts across slip-rings

Peak value of $i_1$ is 7.7 amperes. Resistance of shunt 0.102 ohms

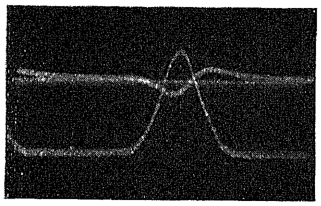


No. 12—50 Amperes Unbalance, Negative Side

Shows total out-of-balance current (lower trace), the oscillograph shunt being put in the neutral wire of the system; and the voltage across the loaded side (upper trace)

The balance leads were connected with no extra resistance in them

The load consisted of a practically non-inductive resistance



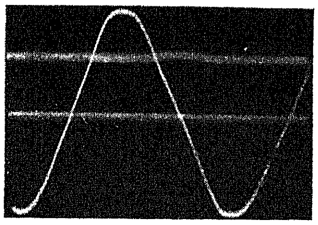
No. 13—76 Amperes Unbalance, Positive Side, 250 Volts D.C.

Shows current in lead *B* and voltage induced in search coil of 30 turns placed around a main pole shoe

The peak value of $i_1$ is 54 amperes

The maximum value of the induced voltage is approximately 0.3 volt. This voltage is due to the decrease in flux which takes place once a cycle due to the armature reaction of $i_1$

It will be noticed that the generation of the e.m.f. persists after the peak in $i_1$ has died to zero

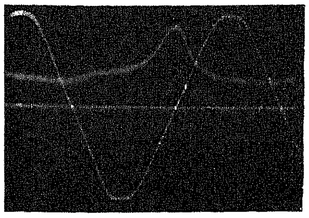


No. 14—76 Amperes Unbalance, Positive Side, 250 Volts D.C.

Shows voltage across slip-rings and field current of machine. No extra resistance in balancer leads

The leads from the oscillograph to the slip-rings in this case have been reversed, so that the voltage wave is upside down when compared with the previous oscillograms

The field current is seen to increase at the instant corresponding to the peak in $i_1$ (compare with No. 13)

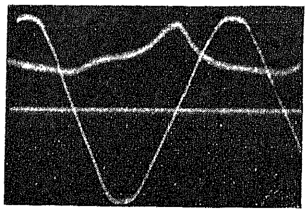


No. 15—Showing Effect of Increased Resistance of Balancer Circuit

In this case extra resistance was put in both phases of the balancer, the total extra resistance in lead *A* being 0.387 ohms, and in lead *B* 0.402 ohms. The ocillogram shows the current in lead *A* and the voltage across slip-rings for a negative unbalance of 3.14 amperes. (The resistance 0.387 ohms of lead *A* is the resistance of the parallel circuit of the oscillograph current strip and the extra resistance introduced into the phase)

The actual peak value of the current $i_1$ is 2.20 amperes, while the extra peak value, as defined in the paper, is 1.81 amperes

Compare this with No. 2 and No. 5



No. 16—Showing Effect of Increased Resistance of Balancer Circuit

In this case extra resistance was again put in each phase of the balancer, the total extra resistance in lead *A* being 1.75 ohms, (this is the resistance of the parallel circuit of a non-inductive rheostat in parallel with the oscillograph current strip), and that in lead *B* 1.81 ohms

The oscillogram shows the current in lead *A* and the voltage across slip-rings for a negative unbalance of 3.11 amperes

The actual peak value of the current $i_1$ is 1.08 amperes, while the extra peak value, as defined in the paper, is only 0.68 amperes

This should be compared with Nos. 2, 5, and 15, from which it will be seen that an increase of resistance of the balancer phases by approximately the same amount in each phase results in an appreciable decrease of the peak current

flux density, which may be calculated from the results in a very simple manner. In Fig. 12 is shown a magnetization curve for the balancer core in question, giving the maximum flux density in kilolines per square inch on a base of peak magnetizing current. This peak magnetizing current is practically the same as the peak values of $i_1$ as measured on the oscillograms, so that in any of the cases shown the maximum flux density may be at once obtained. Taking the maximum peak value shown, 58 amperes (oscillogram No. 7), the maximum flux density in this case is about 133 kilolines per sq. inch, or very nearly double the value for which the core was designed.

These high values of flux density occur only once a cycle, so that the hysteresis loops are considerably displaced, giving rise to increased core losses in the balancer.*

The current peaks in the balancer windings will also increase the copper losses. Taking the same case of oscillogram No. 7, the r.m.s. value of the balancer phase current shown is 27.5 amperes, while that of the current in the other phase (where the peak adds to the direct current component) is 47 amperes. Under normal conditions, with no peak, the current in each phase would be 31.5 amperes, so that the total copper losses in the balancer windings are increased approximately 50 per cent by the presence of the peak, while the copper losses in the phase carrying the larger r.m.s. current are increased no less than 122 per cent.

It is true that in this particular case the peak value of the current $i_1$ is somewhat greater than under conditions of balanced resistance of the phases, since the introduction of the oscillograph shunt has introduced a resistance unbalance in such a way as to increase the peak, but it is clear that these phenomena may give rise to excessive heating of the balancer if the latter is worked at full out-of-balance capacity for any length of time. There will also be an increase of heating in the armature windings, but since each part of the armature circuit only carries half the current $i_1$ and since the full-load current of the armature is very much greater than that of the balancer this effect will not be of very great importance.

It is evident from equation (9) that if the phase resistances of the balancer are unequal, the presence of a large peak in $i_1$ will affect the voltage regulation of the system. For instance, if $R_4$ is greater than $R_3$ the mean value of $(V_2 - V_1)$ will be reduced, but this is at the expense of a larger peak and consequent larger pulsations in the voltages of the system.

It has already been pointed out, in connection with Fig. 8, that the peak value of $i_1$ can be decreased by increasing the value of $(R_a + R_b)$. A certain increase in the resistance of the balancer windings might, therefore, produce a net decrease in the losses. If it should be considered necessary to remove the effect altogether, the logical method would seem to be the use of a compensating winding in the pole-faces of the machine; this could be made to cancel the armature reaction, and so remove the constant term $E_c$ without which the constant term $I_c$ cannot exist. Under such conditions no cumulative effect would take place.

It would not seem that a low maximum flux density in the balancer core is of very much use in preventing the effect, since the growth of the peak needs only a magnetization curve which is not perfectly straight, and this is inevitable even with very low densities.

In conclusion the author wishes to thank Dr. H. Vickers, of the University of British Columbia, for the interest he has taken and the kind encouragement he has given to the progress of this work.

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# Shaping of Magnetization Curves and the Zero Error Current Transformer

BY A. C. SCHWAGER* and V. A. TREAT*
Member, A.I.E.E. Associate, A.I E.E.

## Accuracy Limitations of Electrical Energy Measurements

THE sale of electric power constitutes the basic income of all electric power companies; its purchase is an item of major importance to the consumer. The measurement of power is universally performed by the watthour meter. The amount of capital involved in these transactions makes necessary the measurement with highest possible accuracy. For domestic uses, the accuracy is given by that of the watthour meter, which can be built with errors in the order of one tenth of one per cent. Conditions are different in the case of high-voltage measurements, where the accuracy is given by the combination of watthour meter, current, and potential transformer. The phase angle error of the current transformer is of primary influence. If the ratio error and the errors in the potential transformer are neglected, the following error in a single-phase system operating at a load phase angle $\varphi$, results

$$\Delta P_{per\ cent} = 0.029\ \theta' tg\varphi$$

A current transformer with a phase angle error of 40 minutes at a system power factor of 0.2 causes an error of 5 per cent in power measurement. Such errors can easily occur in the measurements on transformers and induction motors at no load; they assume additional importance with the exchange of power at low system power factor over the steadily increasing number of system interconnections.

## Requirements of the Ideal Current Transformer

*1. Accuracy.* This condition can only be remedied by the more complete elimination of the current transformer errors; these should be reduced to values as they exist in watthour meters. Accuracy limits of 0.1 per cent in ratio and a few minutes in phase angle are required over the entire range of secondary current, that is from 0.5 to 5 amperes.

*2. Burden Capacity.* The capacity shall be high, possibly of the magnitude of 50 volt amperes.

*3. Insulation and Overload Capacity.* In view of the attention which has been given this problem in the past, it will not be necessary to explain it in detail; it is generally recognized that the bushing type current transformer would represent the ideal solution, if it could in addition fulfil requirements 1 and 2.

For this reason a great amount of effort has been spent to improve it with the following major methods now available.

1. Use of high permeability steel.[1,2,3]
2. Brooks' two-stage principle.[4]

Fig. 1 shows the calculated ratio and phase angle curves for various 200/5 ratio bushing type current transformer of 15 in. inside diameter, 18.5 in. outside diameter and 7 in. core height operating at a burden of 15 volt amperes, 100 per cent power factor. *A* represents the ordinary silicon iron core transformer, *B* the high permeability steel core type and *C*, the Brooks' two-stage type used for single element instrument application. None of these transformers meets the accuracy specified in 1 and they are not applicable for metering purposes.

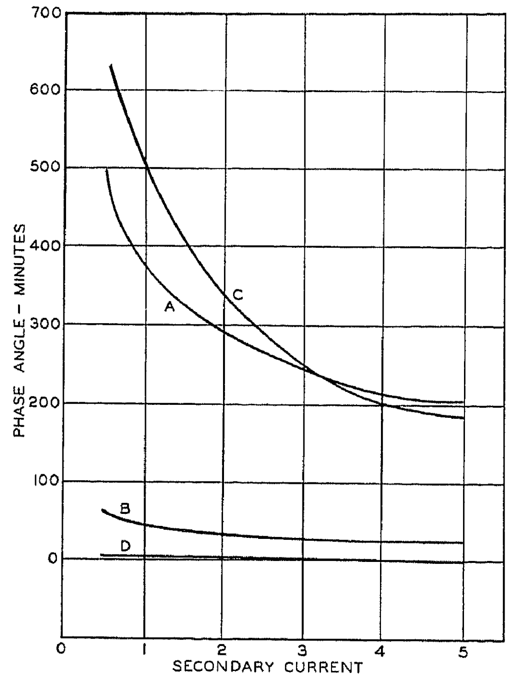

Fig. 1—Phase Angle Errors, 200/5 Ratio, 15 In. Inside Diameter Bushing Type Current Transformer, Burden 15 Voltamperes 100 Per Cent Power Factor

A—Silicon-iron core
B—Nickel-iron core
C—Brooks' two stage
D—Constant permeability core

Curve *D* pertains to a new method of improvement described in this article using a core combination of apparent constant alternating current permeability which makes possible the construction of high-voltage, high-accuracy low-ratio bushing type transformers and which reduces the errors of wound type transformers to

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*Pacific Electric Mfg. Corp., San Francisco, Calif.

1. For references see Bibliography.

*Presented at the Pacific Coast Convention of the A.I.E.E., Vancouver, B. C., August 30-September 2, 1932.*

less than one per cent of their present values. This is accomplished without structural changes to the ordinary transformer; silicon iron is used as core material.

The explanation of the principle of operation is based on the theory of shaping of magnetization curves.

## SHAPING OF MAGNETIZATION CURVES

*The Constant Permeability Transformer.* Since the magnitude of the exciting current is the prime cause of all transformer errors, a reduction in its value is often considered the only means of reducing them. This reasoning is fundamentally wrong as proven, for instance, by the fact that Brooks's two-stage principle for certain conditions is more effective than methods which are based on a simple reduction of the exciting current such as is obtained by the use of nickel iron alloys.

The variations of transformer errors with secondary current, however, are not primarily due to the exciting current, but particularly to the non-proportional relation between exciting current and induction. It is well recognized that a core with proportional flux-exciting current relation would have constant ratio and phase angle errors,[5] which errors could then easily be brought to zero by the application of a resistance or a condenser and by turn compensation. However, the means of producing iron with proportional flux-exciting current relation or expressed otherwise—"with a constant permeability," are not available. It is apparent, however, that a material of constant permeability would be the final solution to the current transformer problem and the following investigation will be along this line and describe the method of obtaining a core of constant permeability.

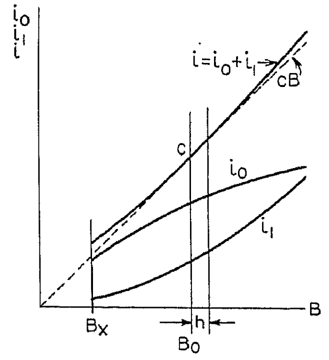


FIG. 2—APPROXIMATION OF STRAIGHT LINE CURVE

Whereas the actual induction-magnetizing current relation is given by curve $i_o$ Fig. 2 the dotted line represents the necessary relation and is mathematically formulated by

$$i_m = \text{constant } B \tag{1}$$

In most technical applications, it will be sufficient for (1) to hold true from values $B_x$ to ten times $B_x$, which range corresponds to the normal operating range of current transformers. Cores of various transformers, naturally, will work over different ranges of induction, corresponding to different initial inductions $B_x$, but for each range, independent of the starting point, complete proportionality is required up to ten times $B$. The $B - i_m$ relation outside this range is not important and no specification will be set up for it, the closer it approaches proportionality, however, the more valuable it will be.

*Molecular Theories of Magnetization.* The problem requires the production of a magnetization curve. Although technical research, by means of alloys and by heat treatment has produced magnetization curves different from the ordinary silicon iron curve, these synthetic methods have not been able to produce the required straight magnetization curve. On the other hand, a solution from the purely scientific side seems too remote although great advancements have been made in the last few years in the explanation of ferromagnetism.

In the following an attempt toward a solution is made by the use of one distinct principle of the molecular theories of magnetization.

Langevin's theory of paramagnetic substances calculates by means of the classical mechanics the magnetization curve and obtains functions which closely approximate those found by experiment. The value of the magnetic induction for each value of the magnetizing force is obtained as the summation of the contributions of the elementary magnets.

Ewing's theory has attempted to explain the magnetization curve of iron as the sum of the magnetization curves of elementary atomic magnets or complexes.

Disregarding the question of the validity of the above theories, they both reveal a principle by which magnetization curves can be produced: by a summation of the magnetization curves of elementary complexes. In the following technical applications this procedure will be denoted as "artificial shaping of magnetization curves."

The elementary complex will be replaced by a small particle of magnetic material, whose magnetization curve will correspond to that of the elementary complex. A great number of particles with individually different magnetization curves will then be investigated in regard to the resulting curve. In particular, it should be possible to choose sizes and curves of the particles in such a way that the resultant magnetization curve is a straight line. The selection of the individual curves for the synthesis of a given function $i = f(B)$ is of great importance, they should present a sufficient functional variety to be of value. It is well known that the magnetization curve of ordinary silicon iron represents a function of continuously varying characteristics. For values of low flux density the curve $i = f(B)$ is concave with regard to the $B$ axis, for higher value it is convex. It cannot be represented as a single function over its entire range, hence it carries in itself the great functional variety required. In the following, a few of the fundamental schemes of shaping of magnetization curves using the silicon iron curve as the basis will be considered; due to the subsequent applications all calculations will be based on alternating currents of a frequency of 60 cycles per second.

### FORMULATION OF MAGNETIZING CURRENT-FLUX RELATION, ADOPTION OF UNIT REFERENCE CORE

In the following, the magnetizing current will be referred to a silicon-iron core of 1 lb. weight and a cross section of 1 sq. in. perpendicular to the lines of force. In a single turn around the smaller cross section neglecting leakage, the following flux-magnetizing current relation exists

*Formula for Low Flux Density.*

$$10 < B < 1{,}000$$

$$i_o = 2.5\,10^{-2}\,B^{0.6} \qquad (2)$$

*Formula for High Flux Density.*

$$3{,}000 < B < 18{,}000$$

The Frohlich-Kennelly relationship[6] states the variation between magnetizing force and induction $B$ for high d-c. fields as follows:

$$\frac{H}{B} = \alpha + \sigma H$$

This relationship holds closely true also for a-c. magnetization curves of silicon iron, giving the following magnetizing current for the unit reference core:

$$i_1/lb = \frac{10}{\dfrac{19{,}300}{B} - 1} \quad 3{,}000 < B < 18{,}000 \qquad (3)$$

### COMBINATION OF A LIMITED NUMBER OF CORES

*Method No. 1.* An ordinary reactor, consisting of a section with a large cross section and of another section with a smaller cross section is representative of this method, see Fig. 3A. For simplicity in calculations a few assumptions will be made. The flux distribution in the small and large cross section will be uniform, leakage flux will be negligible, giving equal total flux in the small and large cross section. The problem thus reduces itself to the considerations of two cores of different cross sections with flux densities inversely proportional to these cross sections. The magnetizing current necessary is equal to the sum of the magnetizing currents which would be required for each section.

As shown in Fig. 3B a unit core of 1 lb. is assumed working at low flux density $B_o$ the magnetizing current $i_o$ thus being given by formula (2). The weight of the core working at high saturation $B_1$ is reduced to $W$ pounds, its current $i_1$, within its limit of application, is given by:

$$i_1 = \frac{10W}{\dfrac{19{,}300}{B_1} - 1} = \frac{10W}{\dfrac{19{,}300}{dB_o} - 1} \qquad (4)$$

Where $d = B_1/B_o$ and is constant.

As shown in Fig. 3B, the cross section of the highly saturated core is equal to $\dfrac{1}{d}$ square in., since the two cores are connected to the same external voltage $E$. The core working at low saturation produces a magnetization curve which is concave with respect to the $B$ axis whereas the highly saturated core produces a curve convex to the $B$ axis. If, now, the weight, $W$, is chosen large, then the character of the resulting $B_o - i$ curve will be determined by the current $i_1$, whereas, for a very small value of $W$, $i_o$ will be the controlling current. In between these two extreme cases, however, there will be a condition which will tend to average the two effects and a curve with a much larger radius of curvature and closer adherence to proportionality can be obtained.

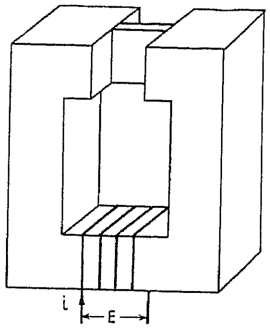


FIG. 3A—TWO-ELEMENT CORE

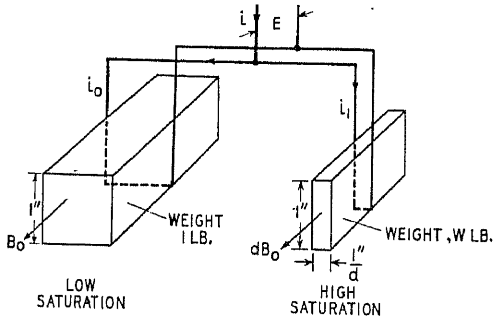


FIG. 3B—EQUIVALENT DIAGRAM FOR TWO-ELEMENT CORE

Fig. 2 shows the result of such an addition, $i_o$ and $i$, being given as functions of $B$ by equations (2) and (4) respectively, the resulting current approximating very closely the straight line $cB$. It is seen that in the neighborhood of point $C$ perfect proportionality is obtained since the tangent to $i_o + i_1$ at the point $C$ passes through the origin. Once proportionality is obtained for one point, it is likely to extend over a considerable range, and the mathematical formulation at one point thus will yield the condition for proportionality over such a range.

*Analytical Solution.* If the value of a function and its derivatives are known for a given point, then this function can be approximated by a potential series in the neighborhood of this point according to Taylor's theorem:

$$f(x_o + h) = f(x_o) + \frac{hf'(X_o)}{1!} + \frac{h^2 f''(x_o)}{2!} + \dots$$

In the following, a sufficient approximation is obtained by using the first two members only. The total magnetizing current per pound of unsaturated core is represented by

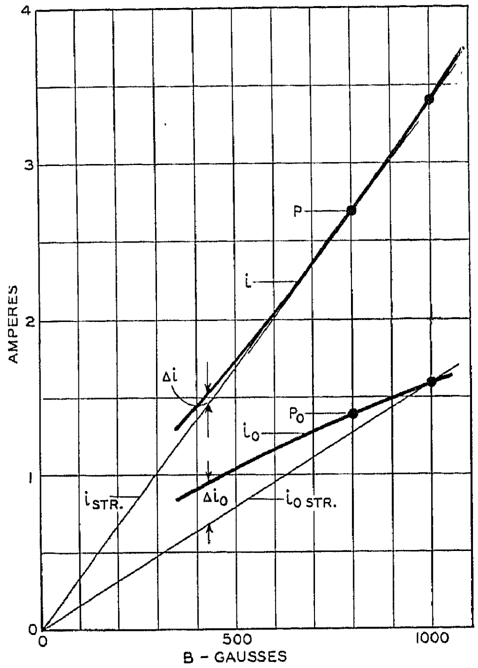


FIG. 4—MAGNETIZING CURRENT

$i_o$ Single-element core
$i$ Two-element core

$$i_o + i_1 = f(B) = 2.5\ 10^{-2} B^{0.6} + \frac{10W}{\frac{19{,}300}{dB_o} - 1} \tag{5}$$

and in the neighborhood of $Bo$ should be equal to $cBo$. The comparison of the coefficients of the Taylor series of these two functions furnishes the following equations.

$$2.5\ 10^{-2} B_o^{0.6} + 10W \frac{Bo}{\frac{19{,}300}{d} - B_o} = cB_o \tag{6}$$

$$1.5\ 10^{-2} B_o^{-0.4} + 10W \frac{\frac{19{,}300}{d}}{\left(\frac{19{,}300}{d} - B_o\right)^2} = c \tag{7}$$

These are the fundamental equations, by which $Bo$, $d$, $W$ and $c$ are connected.

*Example No. 1.* The effectiveness of this method is best illustrated by a practical example. In Fig. 4, $i_o$ represents the magnetizing current of a 1 lb. unit core working over a range from 400 to 1,000 gauss. The additional saturated core is selected to give proportionality for the point $P$, corresponding to $Bo = 800$ gauss, with its respective induction of $B_1 = 6{,}000$ gauss; $d$ is, therefore, equal to 7.5 giving a weight $W = 0.28$ lb. and a coefficient $c = 0.0033$; $i$ represents the total current, the straight line represented by $cB$ is tangent to the curve at 800 gauss. To more easily verify the improvement obtained, a straight line $i_{oStr}$ is drawn through the 1,000 gauss point of $i_o$ and the difference $\Delta i_o$ between $i_o$ and $i_{oStr}$ calculated. In the same manner $\Delta i$ referring to a straight line through the 1,000 gauss point of the $i$ curve, is computed. In Fig. 5, the curves corresponding to $\frac{\Delta i_o}{i_{oStr}}$ and $\frac{\Delta i}{i_{oStr}}$ are shown, the reduction of the value $\frac{\Delta i_o}{i_{oStr}}$ to $\frac{\Delta i}{i_{oStr}}$ is a direct measure of the decrease in the phase angle error for a purely ohmic burden, which can be obtained in a current transformer by the insertion of a highly saturated section into the main core.

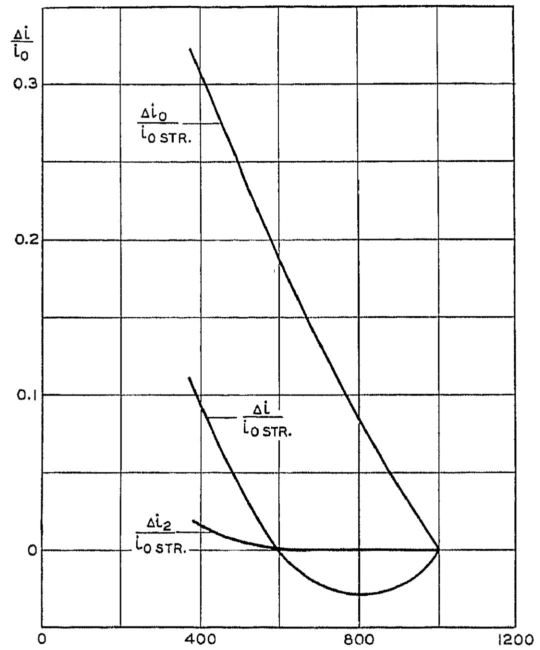


FIG. 5 $\frac{\Delta i}{i_{oStr}}$ FOR VARIOUS CORE COMBINATIONS

*Method No. 2.* In the previous two methods the ratio of the flux densities in the various cores was kept constant. In the following, two cores with a constant ratio of magnetizing ampere-turns will be considered. This condition can be obtained by putting the windings of the two cores in series, see Fig. 6A. The 1 lb. unit core working at the low flux density $Bo$ is wound with one single turn, the other core working at high saturation $B_1$ is assumed to have the same length as the unit core, its cross section is equal to $A$ sq. in. and it is wound with $N$ turns. In this arrangement it is the relation between the applied voltage $E$ and the current $i_2$ which is of primary interest rather than the flux densities $Bo$ and $B_1$. Since the voltage $E$ is directly proportional to the sum of the flux linkages denoted by $\Sigma\Phi_k N_k$ proportionality between these and the current $i_2$ will be formulated.

$$\Sigma\Phi_k N_k = B_o + N \,.\, A \,.\, B_1$$

solving equation (2) for $Bo$ and (4) for $B_1$,

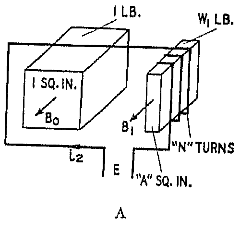
$$\Sigma\Phi_k N_k = 4.56 \;\; 10^2\, i_2^{1.66} + 19{,}300\, AN^2 \frac{i_2}{10 + Ni_2} \qquad (8)$$

and the conditions for proportionality at a point $i_2$

$$4.56 \;\; 10^2\, i_2^{1.66} + \frac{19{,}300\, AN^2 i_2}{10 + Ni_2} = ci_2 \qquad (9)$$

$$7.6 \; 10^2 \; i_2^{0.66} + \frac{193{,}000 \;\, AN^2}{(10 + Ni_2)^2} = c \qquad (10)$$

*Example No. 2.* To make a direct comparison with example No. 1 possible, the current $i_2$ and the number of turns $N$ for the point of proportionality $Po$ will be selected to result in $Bo = 800$ and $B_1 = 6{,}000$, giving



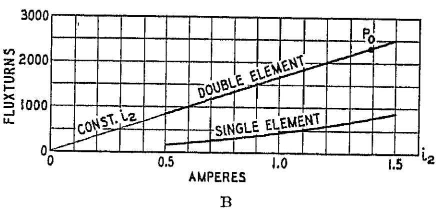


Fig. 6A—Core Combination with Linear Flux Linkage—Magnetizing Current Relation

Fig. 6B—Flux Linkage—Current Relation for Single and Two Element-Core

$$i_2 = 1.38 \text{ amperes}$$

$$N = 3.3$$

The fact that $N$ is a fractional number does not restrict the generality of the calculation. (9) and (10) give $A = 0.076$ sq. in. which number is also equal to the weight of the core in lb. Fig. 6B illustrates the resulting current-flux turn curve. Although proportionality is formulated for the point $Po$, the resultant curve is distinguished by its small deviation from the constant $i_2$ curve over its entire range. This method thus presents a powerful means for producing proportional characteristics. The values $\frac{\Delta i_2}{i_{oStr}}$ are plotted in Fig. 5.

The flux linkage value 2,675 in this example is chosen to coincide with $Bo = 1{,}000$ gauss of the previous example. This curve $\frac{\Delta i_2}{i_{oStr}}$ which is representative of the phase angle variation over the range, shows a great reduction compared to the original $\frac{\Delta i_o}{i_{oStr}}$ curve. From 600 to 1,000 gauss, the variation is practically zero, for the 400 gauss point it is reduced to 5 per cent of the corresponding $\frac{\Delta i_o}{i_{oStr}}$ value. It is also important to notice that for identical flux densities in the 1 lb. unit core, the addition of an exceedingly small saturated core increases by many times the number of flux linkages. The apparent permeability of the combination when referred to the low density core is thus increased accordingly.

## Discussion of Available Transformer Error Correcting Methods

The preceding analysis gives an explanation of certain correcting methods already known. Pfiffner[7] interrupts the main transformer core by a slot producing a portion at high saturation at section $X$, Fig. 7A. In addition he connects a separate reactor core $Y$ of uniform cross section to the secondary winding of the transformer. The principle of operation of this arrangement is identical to method No. 1, previously mentioned in this paper. An arrangement proposed by Wilson, Fig. 7B, provides a hole in the main core through which the secondary winding is linked a sufficient number of times to produce high saturation in the portion embraced.[8] The A.E.G.[9] (Allgemeine Elektrizitats Gesellschaft) on its newest high-voltage transformer uses a core arrangement shown in Fig. 7C. Besides embracing the central core part which works at low saturation, an unequal number of secondary turns is wound on the outside legs, producing high saturation. Fig. 7D shows a similar method introduced by Wellings and Mayo.[10] The operation of these arrangements is easily explained by method No. 2 or a combination of methods Nos. 1 and 2.

However, the improvement obtained by any of these methods is limited, according to published results, hardly exceeding a reduction of the errors to more than 50 per cent. An application of any of the above methods to bushing type current transformers for metering purposes would thus not be practical, since there, a reduction of the errors to one per cent or less is required.

## Infinite Number of Cores

In the foregoing analysis, the magnetization curves resulting from the combination of a finite number of cores, have been investigated. Proportionality has been improved but not completely accomplished. Complete proportionality, however, can be obtained if an infinite number of cores is chosen, in analogy with the production of nature's magnetization curves, each infinitesimal core working at a different flux density. Whereas, in the previous calculation only flux densities were considered which were given by simple analytical formulas, cores working at any part of the magnetization curve are permissible, to produce a greater functional variety.

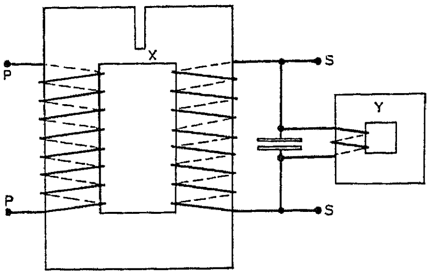


FIG. 7A—IMPROVED TRANSFORMER
Pfiffner

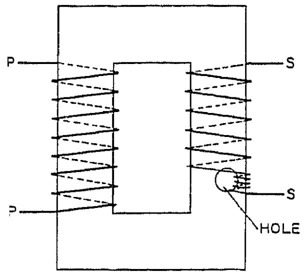


FIG. 7B—IMPROVED TRANSFORMER
Wilson

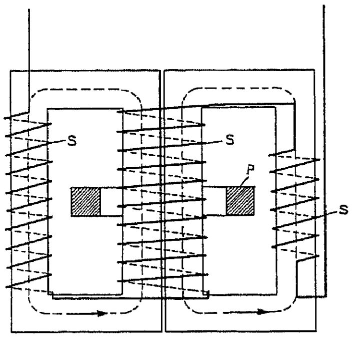


FIG. 7C—IMPROVED TRANSFORMER
A.E.G. (Allgemeine Elektrizitats Gesellschaft)

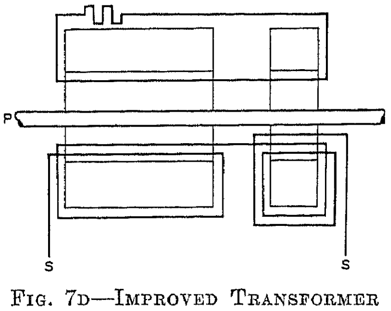


FIG. 7D—IMPROVED TRANSFORMER
Wellings and Mayo

A core of wedge shape such as represented in solid lines, Fig. 8, can be expected to fulfil the requirements. For simplicity it is assumed that the entire flux $Bo$ which enters on the $x$ axis is forced to $x = L$ without leakage and with equal distribution over each cross section. If the reactive voltamperes are represented by $RVA$/lb. $= f(B)$, the specific gravity denoted $s$, it follows

$$dW = 2ydxs$$

$$RVA = 2s \int_0^L y f\left(\frac{B_o}{y}\right) dx$$

and since proportionality between the magnetizing current and the flux is equivalent to a proportionality between $RVA$ and $Bo^2$

$$cB_o^2 = \int_0^L y f\left(\frac{B_o}{y}\right) dx \qquad (11)$$

The solutions of this equation determine the various possible shapes of the wedge $f\ (xy) = o$. Since $RVA$ per lb. $= f(B)$ is not known analytically over its entire range, a general solution is not possible and even if it were known, great difficulties would confront an attempt at such a solution, the determination of $f(xy) = o$ to give a certain $B - i$ relation is best accomplished by test.

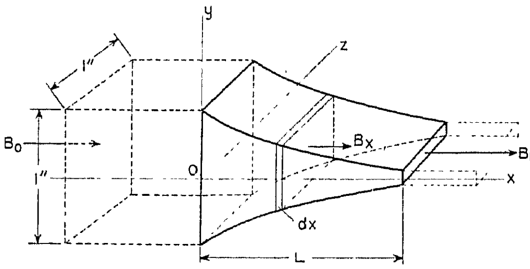


FIG. 8—CORE SHAPE PRODUCING REQUIRED FLUX—MAGNETIZING CURRENT RELATION

For this purpose a reactor was built whose otherwise uniform cross section was interrupted by a portion of varying cross section; to be able easily to vary $f(xy)$, laminations of ordinary transformer iron properly staggered are used.*

## THE ZERO ERROR CURRENT TRANSFORMER[11]

*Practical Construction.* All the necessary requirements for a zero error transformer being available, the most practical and economical construction has to be determined. This applies particularly to the location of the highly saturated portion; it has been previously stated that its weight must be very small to produce proportionality over the entire operating range, and means for easy initial adjustment should be available. The interruption of a core of a weight of several hundred pounds by one or a few laminations as shown in Fig. 7A, which in addition have to be properly staggered, is not mechanically feasible. Slight forces might change the adjustment and produce excessive errors. The arrangement Fig. 7B has similar disadvantages, provides poor means for adjustments and complicates the wiring and insulation of the secondary winding.

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*It was found that permeabilities constant within one-half of one per cent can easily be obtained over a flux density range from $B_o$ to $10B_o$.

If the reactor $Y$ in Fig. 7A is provided with parts working at different degrees of high saturation, it will be capable of producing proportionality without interrupting the main core by a slot, which provided high saturation at $X$. The reactor will have to be provided with a portion working at low flux density, bringing the flux to the constricted section.

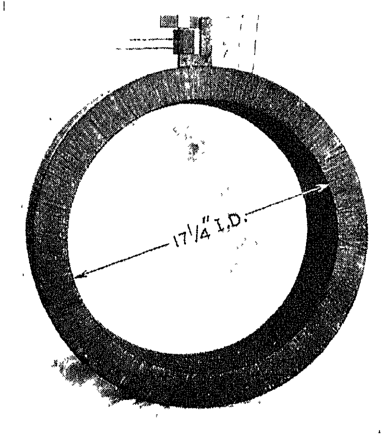

Fig. 9—270-Lb. Bushing Type Transformer Combined with Its Compensating Reactor

The advantages of this construction are apparent, since a small reactor of a weight of a few pounds in addition to a resistance or a capacitance is all that is required to transform any ordinary wound or bushing type current transformer into a zero error transformer. Adjustment of the laminations can be accomplished with ease. The reactor can be mounted directly on the transformer, or placed in any convenient location remotely from it, a feature which is particularly valuable for bushing type current transformers. Fig. 9 shows the combination of an actual bushing type current transformer core 17¼ in. inside diameter, 21¾ in. outside diameter, 7 in. high weighing 270 lb., and its compensating reactor. Its extremely small proportion is clearly visible.

All bushing type current transformers with low ratios are sensitive to a change in the secondary burden. There seems to be no simple means for the elimination of this sensitivity, since it is inversely proportional to the square of the number of secondary turns. Due to the fact that high accuracy can be obtained for very high secondary burdens, for instance, 50 volt amperes and over, an entirely new possibility presents itself.

The great disadvantage of all improved bushing type transformers is not the necessity of their requiring a laboratory calibration with the instruments to be connected, but the extremely low limit of the secondary burden to produce metering accuracy.

Frequent changes in the secondary burdens are made in certain specific cases, but can be considered the exception; the essential feature, however, is the possibility of making the transformer applicable for use over a great range of secondary burden possibly up to 50 volt amperes. This can be accomplished by the addition of a compensating burden, consisting of subdivided resistances and reactances.

The transformer is calibrated for a definite total burden of 50 voltamperes, 50 per cent power factor. In the case of an external burden of 20 voltamperes, 50 per cent power factor, resistances and reactances of the compensating burden have to furnish the missing 30 voltamperes, 50 per cent power factor.

For the purpose of verifying the calculated characteristics the performance of a specific transformer was determined. To keep the investigation in the range of highest voltages and the most frequent currents, the transformer shown in Fig. 9, arranged for 400/5 and 200/5 ratio was investigated.

Most tests were performed by means of a test primary wound onto the bushing type transformer core, the turns being equal to the theoretical number of secondary turns, that is 80 turns for a 400/5 transformer.[12] This allows the use of comparative test equipment, such as a Silsbee set, without the necessity of a standard transformer or accounting for its errors. Testing is greatly simplified also, because a loading transformer is not necessary. Considered from the standpoint of field testing, the elimination of the standard and loading transformers will reduce the weight of equipment at least 80 per cent and save considerable time and risk. Results will be improved in accuracy by the elimination of the standard transformer since a fully distributed test winding has been

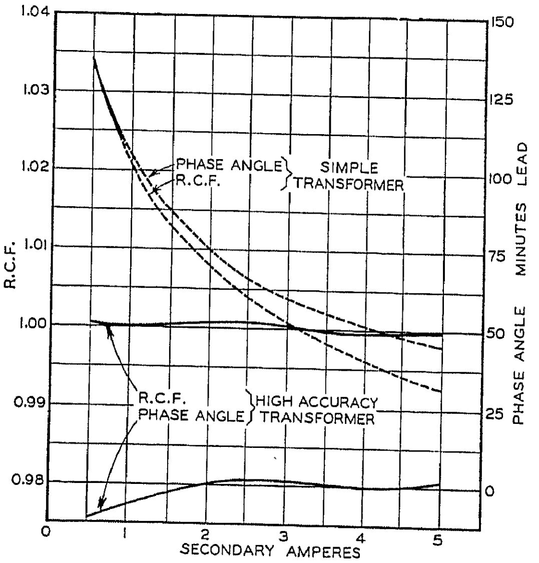

Fig. 10—Bushing Type Current Transformer 400-5, 60 Cycles

Internal diameter 17¼ in. (43.8 cm.); weight 270 lb. (122.5 kg.); external burden 50 voltamperes, 0.50 power factor found to be equivalent to a single central conductor by Knopp, and many others.[10,12,13] The equipment of bushing type current transformers with such a test primary is strongly recommended when they are to be used for metering purposes.

Fig. 10 gives ratio correction factor and phase angle characteristics for a 115-kv. bushing type current transformer with and without the transformer compensator, the high accuracy curve is plotted from points taken by an absolute (precision) test method. These data are given in tabular form in Table I.

TABLE I—TABULATION OF HIGH ACCURACY CHARACTERISTICS AS PLOTTED IN FIG. 10

| Secondary amperes | Ratio correction factor | Phase angle in minutes (+) indicates leading |
|---|---|---|
| 0.5 | 1.0006 | −11. |
| 1.0 | 1.0001 | − 7. |
| 2.0 | 1.0007 | 0. |
| 3.0 | 1.0004 | + 1. |
| 4.0 | 1.0000 | 0. |
| 5.0 | 0.9999 | + 1. |

Characteristic curves are insufficient to define the all around accuracy of a current transformer. Its sensitivity to burden and thermal changes is also necessary and Table II gives these values for the high accuracy transformer on its 400/5 ratio.

TABLE II—HIGH ACCURACY 115-KV. BUSHING TYPE CURRENT TRANSFORMER 400-5. INTERNAL DIAMETER 17¼ IN. (43.8 CM.), WEIGHT 270 LB. (122.5 KG.), BURDEN 50 VOLTAMPERES, POWER FACTOR 0.50

| Due to: | Maximum increment in ratio correction factor. (+) indicates increase | Maximum increment in phase angle in minutes. (+) indicates leading |
|---|---|---|
| Temperature rise of 10 deg. cent. of transformer and transformer compensator | +0.0001 | +1. |
| 1.0 voltampere increase in burden (resistive) | +0.0007 | +6. |
| 1.0 voltampere increase in burden (reactive) | +0.0013 | −3. |

Wound type current transformers equipped with the device described will show improvement comparable to that of the bushing type. In a specific case, a simple 69-kv. wound type, with a burden of 50 voltamperes and secondary current range of 0.5 to 5 amperes has a variation in error of 0.008 in ratio correction factor and 13 minutes of phase angle. This transformer under the same conditions can be improved in characteristics so that its maximum errors are within the accuracy of commercial test equipment; namely, 0.001 in ratio correction factor and 3 minutes of phase angle. Further improvement is possible but is not considered to be of commercial value.

### CONCLUSION

1. The improvements described have brought low ratio silicon-iron core bushing type transformers into a range of accurate performance sufficient for metering, approaching that of a watthour meter.
2. Although extra circuits and equipment are required, they are not on the transformer itself and are readily accessible.
3. The useful burden on the transformer may be large and changed to a considerable degree with no appreciable effects on the transformer calibration, providing proper adjustment is made in a burden compensator.

### ACKNOWLEDGMENT

The authors wish to express their appreciation of the advice and encouragement given them by Mr. Roy Wilkins and of the assistance in tests and computations by Mr. J. K. Siewertsen.

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## Discussion

**G. Camilli:** It appears to me that the characteristic curve *C* shown in Fig. 1 is misleading, in that it does not represent the approved method of application of the two-stage principle. According to this curve, it looks as though phase angle of the Brooks' two-stage current transformer (curve *C*, Fig. 1) is worse than that obtained by the simple uncompensated current transformer.

I have no doubt that the authors have actually obtained their curve *C* with the design and arrangement that they set up, but, apparently, their set up was not such as to produce the best results which the two-stage principle is capable of. The following presents data on a two-stage unit that is more representative:

*Modified Two-Stage Bushing Type Current Transformer for 132-Kv Bushing.* Dimensions of the main secondary core (silicon steel) were as follows:

Inside diameter = 18 in.
Outside diameter = 24½ in.
Height = 4 in.
Weight = 195 lb

The tertiary core had the same dimensions as the main core with the exception that its height was only $1\frac{1}{2}$ in. This core was made of permalloy 0.014 in. in thickness and was formed by winding up strips which previously had been spot welded. The weight of this core was 59 lb.

The following tests were made at 100 amp, primary current. Total secondary burden 1.0 ohm at 0.69 power factor, plus 1 amp G.E. I-16 element. Tertiary burden 0.44 ohm at 1.0 power factor plus 1 amp G.E. I-16 element.

| % primary current | Ratio correction factor | Phase angle |
|---|---|---|
| 100 | 1.0010 | +15′ |
| 60 | 1.0018 | +12.5′ |
| 20 | 1.0018 | + 3.2′ |
| 10 | 0.9997 | − 5.8′ |

It might be pointed out that the above results were obtained with the current transformer under such unfavorable conditions as a primary current one-half of that used by the authors and a length of magnetic circuit 1.25 times as large. Favorable elements were somewhat larger cross section and apparently smaller burden.

This variance may make a comparison difficult, but they are irrelevant to the point I wish to make, namely, that excellent results may be obtained by a judicious design and application of the two-stage principle.

An important consideration in obtaining the utmost from the modified two-stage principle is to two-stage only the wattmeter current coil (excluding ammeters, relays and any other series impedance) and then to compensate only for the wattmeter current coil.

**A. C. Schwager and V. A. Treat:** Mr. Camilli has given an excellent example illustrating the high accuracy now available with high voltage bushing type transformers of low ratio. We regret that space limitations made it necessary to omit a more thorough discussion on the two-stage and modified two-stage principle, in which the corrective ability of these methods was more fully shown, and the favorable results for high ratios or low burdens have been pointed out. The reader is referred to the publication: "Der Fehlerlose Stromwandler," by A. C. Schwager, *Bulletin des Schweizerischen Elektrotechnischen Vereins*, No. 20, 1932 where most correcting methods known have been treated analytically; the calculations and data given below are based on the formulas developed in this publication.

From Mr. Camilli's discussion it appears as if the favorable results obtained by him were due entirely to the application of the modified two-stage principle; this viewpoint as well as the comparison with our 200/5 ratio transformer are misleading. In the following it will be shown that the improvement obtained by him is only to a small portion due to the two-stage principle, the larger portion being brought about by two additional methods of correction, distinctly different from the two-stage principle. To identify his transformer as two-stage transformer therefore remains a matter of designation only, the improvement over an ordinary silicon iron transformer has to be analyzed on the basis of additional methods. Both of these methods are well known and in general use; one, is the use of instruments with a normal full current rating of 1 ampere, and the other is the application of a high permeability nickel iron core material.

### METHOD NO. 1

*Instruments with 1 Ampere Full Current Rating.* It is well known that in outdoor metering installations using 5 ampere normal current, the resistance due to the leads from the transformers to the watthourmeter constitutes the largest part of the burden. Taking the data from Mr. Camilli's tertiary circuit it is seen that the leads at 5 amperes would absorb 0.44 × 25 = 11 watts, whereas the watthourmeter draws 1.3 va only. If the normal full load current is reduced to 1 ampere then these leads consume only 0.44 watt, the wattmeter still requiring 1.3 va. In the following calculations these 1.3 va will be assumed at 100 per cent power factor, the phase angles computed in this manner will be slightly larger than the actual ones and favoring Mr. Camilli's transformer in a comparison.

In the publication mentioned above the phase angle error of a transformer with a ratio of outside to inside diameter of 1.25 operated at a purely ohmic burden $r$ is given by:

$$tg\,\theta \cong \theta = 1.77.10^{12}\,\frac{s\,\gamma_{\mathrm{M}} D^{0.4}\,r^{0.6}}{H^{0.6}\,N^{1.6}\,I_2^{0.4}} \qquad (1)$$

Where $s$ = specific gravity in lb/in.$^3$

$$\gamma_{\mathrm{M}} = \frac{RVA/16}{B^{1.6}} = \left\{ \frac{4.3\ 10^{-7}\text{ for silicon iron}}{4.4\ 10^{-8}\text{ for nickel iron}} \right.$$

$D$ = inside diameter of core in inches
$H$ = height of core in inches
$N$ = number of secondary turns
$r$ = resistance of secondary burden in ohms
$I_2$ = secondary current in amperes.

In all the following discussions we assume $D$ = 15 in., $H$ = 7 in. An ordinary 100/5 amp silicon core transformer with a purely ohmic secondary burden of 12.3 watts (0.49 ohms) according to the above equation has an error of approximately 1,300 minutes (21 degree). Using a 100/1 amp transformer however, reduces the error to 400 minutes. The great improvement obtained for identical secondary resistance by the use of a 1 amp normal current current transformer is apparent.

### METHOD NO. 2

*Use of Nickel Iron Alloys as Core Material.* The value of high permeability nickel iron alloys as core material is generally recognized. By its use the phase angle errors for an ohmic burden can be reduced to 1/10th the value of those of the corresponding silicon core transformer. If the silicon core of the 100/1 amp transformer considered above would be replaced by a Ni-Fe core, the error of 400 minutes could be reduced to 40 minutes. The powerful corrective capacity of a combination of scheme I and II is apparent since it brings about a reduction from 1,300 to 40 minutes (approximately 32 times), leaving errors higher but of the same magnitude as given for Mr. Camilli's transformer.

### METHOD NO. 3

*The Two-Stage Principle.* The Brooks' two-stage principle represents one of the most fundamental methods of reducing errors. If the errors in the first stage are inherently small (for instance, of the magnitude of 60 minutes in phase angle or 1 per cent in ratio, or less), then the correction due to the second stage is considerable, a reduction of the errors by 5 to 10 times can be satisfactorily accomplished. The method is particularly useful for standard transformers. As soon as the errors in the first stage become excessive (of the order of several degrees in phase angle or several per cent in ratio) due to a large burden or a low transformer ratio, the corrective ability of the original two-stage and particularly that of the modified two-stage (due to the doubled burden) is rapidly lost as shown by curve $C$ of our Fig. 1 referred to by Mr. Camilli.

### COMBINATIONS OF METHODS 1, 2 AND 3

It is evident that the application of the two-stage principle to a Ni-Fe core would produce a radical improvement. Economical consideration however makes it advisable to restrict its application to the auxiliary core only. The use of these two principles alone however is not capable of producing the necessary accuracy. This fact is very definitely illustrated by test made by the A.E.G.[1] where a 200/5 A transformer at 15 va, 100 per cent power factor using the modified two-stage principle with auxiliary Ni-Fe core reduces phase angle errors only 5 times. The corrected transformer still shows an error in excess of 100 minutes at 10 per cent secondary current. In this way satisfactory results cannot be obtained.

The additional necessary improvement has to be brought about by another principle, which corresponds to our method 1, using 1 ampere normal full current. The proper combination of scheme 1, 2 and 3 is then sufficient to bring about the accuracy required and shown in tabular form by Mr. Camilli.

### METHOD NO. 4

*Use of Constant Permeability Core.* The method of shaping magnetization curves described by us gives an additional independent means of reducing the errors. Since the reduction due to the apparent constant permeability of the main and reactor core combination is approximately 100 times in ratio and phase angle, the errors of the ordinary 100/5 amp silicon core transformer are reduced from 1,300 minutes to approximately 13 minutes. This method is therefore capable of producing in one step the improvement that a combination of 1, 2 and 3 is able to yield. Standard instruments can be used, the use of the expensive Ni-Fe alloy core is eliminated and there are no complications due to the splitting up of the core in sections to allow the use of the two-stage principle. The advantages in initial cost and simplicity in operation are apparent since this method, in addition to the ordinary core and winding, requires but a small reactor of approximately one pound weight and a resistance or a capacitance.

### COMBINATION OF METHOD NO. 4 WITH METHODS 1, 2 AND 3

Whereas Mr. Camilli's transformer has already used the first three mentioned correcting methods, these can now be applied to the constant permeability transformer. If the 100/5 transformer considered in Method No. 4 is changed into a 100/1 transformer, the resulting phase angle error will not be in excess of 5 minutes, a result which is easily verified by equation (1). This transformer makes possible a direct comparison with the errors listed for Mr. Camilli's 132-kv transformers. Since the phase angle error in his case is 15 minutes it is evident that our 100/1 transformer with a maximum error of 5 ft is greatly superior to Mr. Camilli's transformer. This comparison is justified since Mr. Camilli's transformer also operates at 1 amp normal full current; his comparison with our 200/5 ratio transformer is therefore misleading.

If the core of our 100/1 transformer is replaced by a Ni-Fe core a 25/1 transformer with an error not exceeding 5 ft results. Without the use of the constant permeability principle such accuracies at low ratios cannot be obtained by any other correcting method, and it therefore opens an entirely new field of application for bushing type transformers. Still lower ratios could be obtained by the additional application of the two-stage principle, although the demand for them is less pronounced.

The two-stage principle however is capable of producing improvements on low ratio transformers which are more important than a further reduction in ratio, and in the future promise it a wide field of application. All low ratio current transformers, (such as our 25/1 or Mr. Camilli's 100/1) are sensitive to burden changes. These transformers have to be given an accurate calibration with the instruments and leads with which they are used. Temperature changes in the resistance of the watthourmeters can cause a sufficient variation in burden to slightly impair the otherwise high accuracy. With the original Brooks' two-stage principle goes the ability to correct automatically the two-dimensional multiplicity of current—as well as burden changes. This latter feature makes it possible to produce transformers practically insensitive to such unavoidable burden changes and it can be applied with success on the lowest ratio transformers; the necessary use of two-stage meters should not prevent its general application to such cases. The modified two-stage principle, using single element instruments unfortunately is not capable of correcting the burden variation, a fact which is easily overlooked.

### WOUND TYPE TRANSFORMERS

In spite of the progress made in the design of accurate bushing type current transformers, the wound type transformer will maintain a limited field of application. It will fill the gap for the lowest ratios, such as 5/5 to 100/5, and will also be used in all cases where insensitivity to fairly large burden variation is imperative, such as due to changes in the number of instruments connected. Such transformers, particularly for highest voltages, due to the large amount of iron used, still show relatively large inherent errors, such as 30 to 60 minutes in phase angle and 0.25 to 0.5 per cent in ratio. Such errors are excessive in all cases where large blocks of power are measured, as in the case of system interconnections.

These errors can be reduced to less than 10 minutes in phase angle and 0.1 per cent in ratio by any of the four correcting methods described. Whereas 1, 2 and 3 would require special instruments, expensive core material or complicated core construction, respectively, the Method No. 4 illustrated by the authors brings about the required correction at practically no additional cost or complication and seems advisable in all cases. It is even possible to reduce the errors of any installed wound transformers to practically zero by the simple addition of the small reactor and a resistance or capacitance.

In conclusion we hope that this discussion has clearly analyzed the improvements obtained by Mr. Camilli and given a more justified comparison between the various methods of improvements of current transformers.

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[1] J. Goldstein, "Die neveste Entwicklung im Stromwanderbau," *E.T.Z.*, Volume 18, 1932, p. 429.

# Corona Loss Measurements for the Design of Transmission Lines to Operate at Voltages Between 220 Kv. and 330 Kv.

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and

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***Synopsis.**—Corona loss measurements were obtained on conductors of three different diameters; namely, 1.125 in., 1.49 in. and 2.0 in. Voltages up to 600-kv. line voltage were used in these measurements. Various surface conditions of the 1.125-in. cable were studied. These measurements include tests on the new cable as received, the cable as washed, scratch brushed, buffed and dragged. The aging of the dragged cable was observed for seven months. Data were obtained on the daily variation of loss. The effects of configuration and transposition were studied on No. 2 wire. A description of the modifications in the high-voltage wattmeter for these high-voltage measurements is reported.*

* * * * *

## INTRODUCTION

DURING the summer and fall of 1931, measurements at the Harris J. Ryan Laboratory, Stanford University, extended the range of corona loss data for conductor sizes beyond those investigated during 1930, the results of which were presented in an A.I.E.E. paper.[1] This investigation was made possible by the Department of Water and Power, City of Los Angeles, and the results of this investigation are being used in the economic study of the transmission of Boulder Canyon power to the City of Los Angeles.

The three conductor specimens studied in these tests were a 1.125-in. hollow copper cable, a 1.49-in. hollow copper cable and a 2.0-in. hollow aluminum cable. See appendix I. The losses were measured on a three-phase line 700 ft. long. Voltages as high as 600 kv. between lines were used.

## GENERAL DESCRIPTION OF LAYOUT

For the comparison of losses the different conductor specimens were always mounted in a horizontal configuration with a clearance to ground of 30 ft. and a sag of 16 ft. The spacing was such that the ratio of $S/r$ was practically the same for all the tests except that of the 2.0-in. conductor in which for good clearance the physical dimensions limited the spacing to 30 ft. For the method of supporting conductors, see reference 1.

Certain variations of the loss due to the surface condition of the conductor had been found by previous test, but it was desired to carry on such tests over a wider range of conditions, such as scratch brushing and polishing the conductor, which gave an ideal surface; and dragging the conductor, which left it more nearly the same as found in actual practise.

Since so much depends on the surface condition of the conductor, considerable care was taken in the handling of the specimens. For example, the new 1.49-in. cable that was shipped from the factory on one reel was rewound onto three smaller reels. As it was rewound, it was carefully taped with heavy wrapping paper. In the process of erection the reels were mounted on a truck in a frame, and the cable was paid out from the truck along on the dry ground directly under the insulator supports. The clamps were put on, and as the cable left the ground the paper was removed. This left the cable almost in the identical condition it was when it left the factory. When the 1.125-in. cable was lowered for washing, scratch brushing or buffing, it was not allowed to touch the ground. This was accomplished by means of heavy wooden horses about 4 ft. high. These horses were placed from 50-ft. to 60-ft. apart. At the top of each horse was a wooden roller which allowed the conductors to move freely without being scratched and without danger of the horses being pulled over. To preserve the clean and polished surface of the 1.125-in. cable, it was also taped with heavy paper immediately after scratch brushing and buffing. This wrapping was not removed until the cable was being erected just before test.

The insulator strings used on the 1.125-in. cable were of 18 units, 10-in. diameter, and were shielded at the lower end with a Koontz type shield. The insulator strings for the 1.49-in. and the 2.0-in. cable were similar, but were shielded on each end by means of an aluminum ring radio shield. See Fig. 10. The diameter of the tube of which this ring was made was 2.5 in. and the large diameter of the ring was 22 inches.

The voltage was applied to the line by means of three 350-kv., 350-kva. transformers Y-connected on the high-voltage side, and delta-connected on the low-voltage, or 2,300-volt side. These transformers were energized from a 2,300-volt sine-wave alternator.

Fundamentally, there was no difference in the method of making these measurements from those reported in the former paper. Briefly, this measuring method involved the use of three single-phase, high-voltage wattmeters, each being connected directly between one

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[1] See Bibliography.

*Presented at the Pacific Coast Convention of the A.I.E.E., Vancouver, B. C., August 30-September 2, 1932.*

line and ground. Dynamometer type meters were used. The line was fed directly through the current coil of the meter, and the potential coil was connected directly between line and ground by means of a high-voltage, water resistor multiplier.

Certain modifications in the former measuring equipment were necessary in order that satisfactory tests be carried on with the larger conductors. One change was the mounting of the test specimen nearer the laboratory, thereby reducing the length of the shielded wattmeter lead from 450 ft. to 100 ft. This reduced the error caused by the capacitance between the lead and shield shunting the field coil of the wattmeter to a negligible value up to the highest voltage used. The description of the 350-kv. wattmeter multiplier is given below.

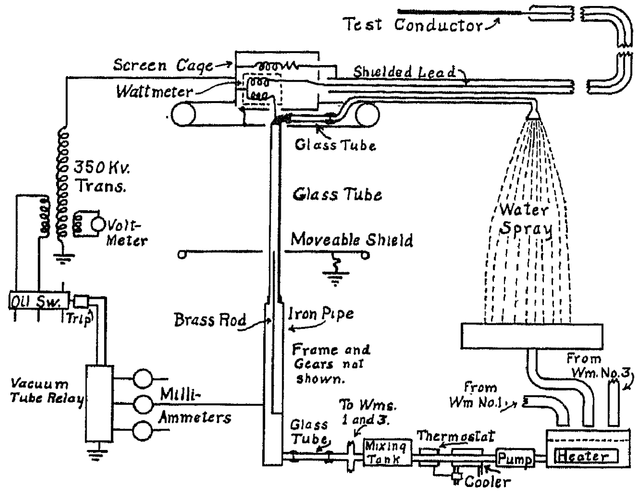

FIG. 1—WATTMETER CONNECTIONS

## HIGH-VOLTAGE WATTMETER MULTIPLIER

This multiplier consisted of a glass tube 0.4-in. inside diameter and 1/16-in. glass, mounted between two circular, iron mesh shields four feet in diameter. The lower shield was mounted on a movable frame work actuated by screws. The upper shield was supported by means of redwood sticks 1½ in. in diameter. These sticks were dried out in an oven at a temperature of approximately 110 deg. cent. until they showed no further decrease in weight. They were then placed in a bath of paraffin at this same temperature, the paraffin was allowed to cool until it began to solidify and then the sticks were removed having a thick coating of paraffin on the outside. When completely cooled, the excess paraffin was carefully removed. This gave a dry insulating support sealed against absorption of moisture. This support was better than Bakelite or similar insulation, because of its lower dielectric constant requiring less charging current; and at the same time, disturbing to a lesser degree, the field about the water resistor.

Mounted on the edge of the upper shield was a torus six inches in diameter which showed no signs of corona at 350 kv. Inside the glass tube was arranged a brass rod 1/8 in. in diameter. This rod was mounted in a water-tight cylinder below the lower shield in such a manner that it moved upward by means of a screw arrangement at the same rate as the lower shield. With such an arrangement, the shield and the brass rod moving together, the resistance of the multiplier could be changed uniformly and have correct shielding at all times. A schematic diagram of the equipment is given in Fig. 1 and the high-voltage multiplier is shown in Fig. 2. Distilled water was circulated through the glass tubes of the three multipliers by means of a pump, the water being discharged at the high-voltage end through a spray similar to the method used in previous measurements. By the use of the distilled water a multiplier of minimum length could be made, reducing the capacitance of the resistor to the shields and to ground to a minimum. For this reason, if the voltage distribution along the resistor did not conform exactly to the field between the shielding plates the error introduced by the charging current from the resistor would be extremely small because of the resistor dimensions. At 350 kv. and with 50 milliamperes of current there are 17.5 kw. of energy absorbed by the resistor. To prevent excessive rise in temperature the water flows through each resistor at the rate of 5 gallons per minute. This gives a temperature rise up the water column of 13 deg. cent. To reduce the error introduced by the change in resistance of the water due to increase in temperature, the water entering the resistor was maintained by means of thermostat control at a temperature of 40 deg. cent. At this temperature, the energy dissipated due to evaporation in the spray is approximately 5 kw.; so that at low voltages the energy absorbed by the multiplier was less than that dissipated in the spray. In order to maintain this 40 deg. cent. temperature it was necessary to heat the water before it entered the multiplier. At the higher voltages the energy absorbed by the multiplier was greater than that dissipated by the spray. Under these conditions it was necessary to

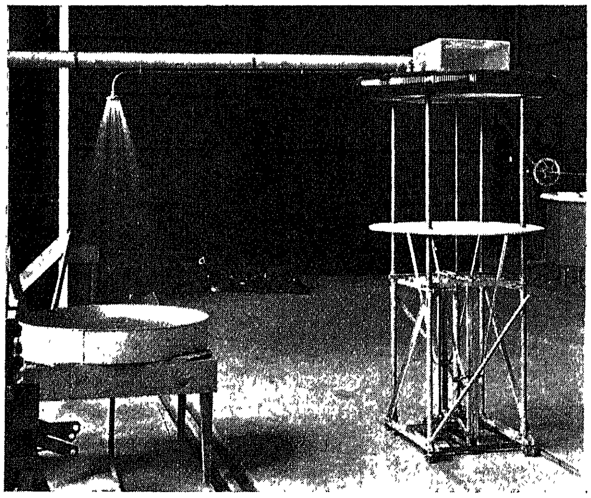

FIG. 2—HIGH-VOLTAGE WATTMETER MULTIPLIER

cool the water. This was done by means of a water cooling coil.

As the water is circulated through the system it picks up certain impurities and in time the resistance lowers sufficiently to necessitate some adjustment. This adjustment of the resistance of the water was accomplished by means of an arrangement, the principle of which was observed before the wattmeter was built. By passing the water between plates of aluminum and carbon with d-c. potential of 125 volts between the plates, the aluminum being positive, the resistance of the water was found to increase considerably and in some cases it was possible to increase it as much as five times its original value.

The wattmeter instruments were protected by means of low-voltage safety gaps across their coils and also by a special vacuum tube relay in the ground end of the multiplier.

### MEASUREMENTS

At the beginning of this test the engineers on the project said that it would be their aim to keep the corona loss a minimum within reasonable limits of conductor cost. A loss value of ½ kw. per mile was suggested to be kept in mind, for test purposes. At a voltage of 275 kv. this means a power factor of the test specimen of 0.1 per cent. Such a condition is extremely exacting when it comes to measurements at such high voltages. It was necessary to check carefully all possible sources of error in the measuring equipment and approximate their magnitudes. Such sources included the shielding of the water resistor multiplier, the capacitance between the wattmeter lead and its shield, the wattmeter itself, and the measurement of the voltage.

One of the meters used in the test was calibrated at the Department of Water and Power Testing Laboratory. The other meters were calibrated at the Ryan Laboratory using this meter as a standard. There were no standards conveniently available for use at these extremely low power factors; so a further check by an absolute method was devised. Two similar wattmeters were connected in a circuit so that the mutual inductance of their coils balanced. By means of a condenser in the current coil circuit and a variable inductance in the potential circuit, the current in the potential coil was shifted until it was exactly at right angles to the current through the current coil. This was indicated by zero reading on both of the wattmeters for both direct and reversed readings. The magnitudes of the currents were made of the same order as those on corona tests and were measured by milliammeters. The resistance, inductance and capacitance of the circuit were known. By inserting a small known resistance in the current coil circuit, the phase angle of the current was shifted a small amount from the 90 deg. position. The amount of this shift was computed from the constants of the circuit. For power factors of the order of 0.1 per cent the calibration of the meters was comparable to that at higher power factors, as determined by comparison with standards.

The determination of the line voltage was made from the voltmeter coil of one of the transformers. With the line connected this was carefully checked with the 50-cm. sphere gap, and found to be slightly in error. A calibration curve was taken for the voltmeter coil and the voltage correction was made in all of the computations. A power circuit, harmonic analyzer measurement of the voltmeter coil voltage and also of the current through the high-voltage wattmeter multiplier showed the voltage wave to be very nearly sinusoidal. For example, with the 2.0-in. cable operating at 450-kv. line voltage, the highest harmonic was the fifth, its value being 0.9 per cent. The next highest harmonic was the third with a value of 0.3 per cent. None of the other harmonics were in excess of 0.1 per cent. The magnitude of the harmonics increased slightly as the corona loss was increased by higher voltages.

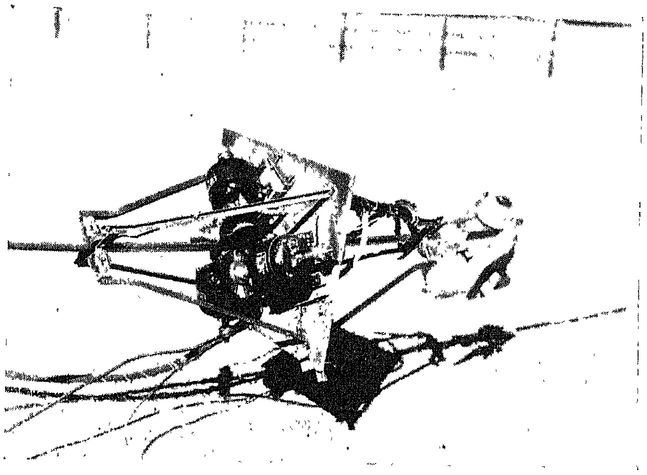

FIG. 3—ASSEMBLY OF BUFFING MOTORS

Measurements of air temperature and humidity were similar to those of previous tests, thermometers being placed in the shade out-of-doors and in the direct air stream from a small fan. However, one addition was made to this equipment; namely, a short specimen of cable with a thermometer mounted on the inside in such a manner that it could be removed and the temperature of the cable read. This cable was always mounted in the sun about six feet above the ground, and the assumption was made that the temperature as recorded here was the same as that of the test specimen.

### DISCUSSION OF RESULTS

During the tests described in this paper, variations in loss were observed during the day that are far in excess of that which could be accounted for by the variation in $\delta$, the air density factor. Further, data now being collected, yet not sufficiently studied to be presented at this time, indicate that the value of $\delta$ should be calculated from the conductor temperature rather than the air temperature, and that the variation of $E_0$ with $\delta$ is not a direct proportion, as previously assumed, but is some other function of the air density factor.

As the volume of data available on corona loss is increased the difficulty of obtaining a formula to fit all of the curves for the conditions involved is more evident. Any one calculating corona loss on lines realizes that the economic range for operating lines is with the conductors of a diameter so that the corona loss is below 10 kw. per mile, and, in many cases, the economic conductor size is such as to give a corona loss of less than 1 kw. per mile. Since these low values of loss are the most needed and since it is in this range that the present existing formulas[2,3] and test results show the greatest deviation, the data given in this paper are presented as recorded with voltage and meter corrections only; no correction for air density having been made.

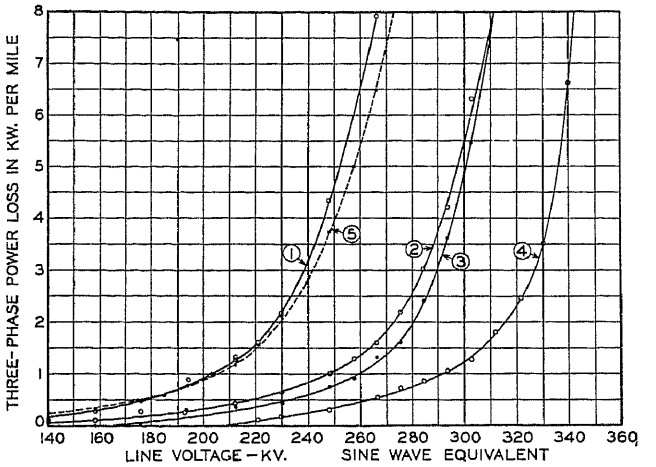

Fig. 4—Corona Loss Curves Showing Effect of Cable Surface

1.125-in. cable—22-ft. horizontal spacing

| Curve No. | Barometer in. hg. | Temperature—deg. fahr.<br>Dry bulb | Wet bulb | Cable | Date | Surface condition |
|---|---|---|---|---|---|---|
| 1 | 29.79 | 77 | 66 | | 8-28-31 | New |
| 2 | 29.84 | 77 | 65 | | 9- 3-31 | Washed |
| 3 | 29.92 | 69 | 59 | 71 | 9-28-31 | Scratch brushed |
| 4 | 29.84 | 72 | 55 | 80 | 10- 3-31 | Buffed |
| 5 | 29.78 | 64.5 | 57 | 66° | 10-13-31 | Dragged |

*Study of Surface Conditions.* As had been found in the previous measurements at the Ryan Laboratory,[1,4] the die grease or other foreign matter that exists on the cable as it is received from the manufacturers causes a very material increase in the corona loss. New cables, washed with gasoline and further washed with a soap solution and thoroughly rinsed with water showed a substantial decrease in loss from that found on the new cable unwashed. All of the cables tested were treated in this manner; namely, tested as received from the factory, or as nearly so as possible, and then thoroughly washed and again tested. In addition to these two surface conditions, the 1.125-in. cable was tested after three other treatments of the surface, namely, scratch brushed, buffed and dragged. The curves for the various surface conditions of the 1.125-in. cable are given in Fig. 4.

Curve No. 1 is the loss as found on the cable when it was first erected. This cable had been stored at the laboratory for three years. Curve No. 2 gives the loss as obtained after the washing treatment. The explanation of the physical change resulting in the very unusual electrical change cannot be given. It has been found to exist wherever new cables have been tested and then washed, and is further evidenced by the very excessive noise on new lines that gradually decreases with aging of the lines.

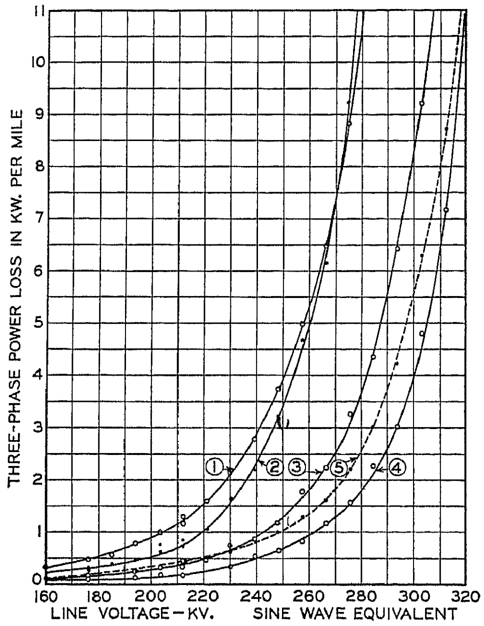

Fig. 5—Corona Loss Curves Showing Aging of Dragged Cable

1.125-in. cable—22-ft. horizontal spacing

| Curve No | Barometer in. hg. | Temperature deg. fahr.<br>Dry bulb | Wet bulb | Cable | Date | Surface condition |
|---|---|---|---|---|---|---|
| 1 | 29.78 | 64.5 | 57 | 66 | 10-13-31 | Dragged |
| 2 | 29.87 | 68 | 58 | 78 | 10-14-31 | Dragged |
| 3 | 30.14 | 60 | 56 | 78 | 12- 4-31 | Dragged |
| 4 | 30.17 | 60 | 50 | 68 | 1- 6-32 | Dragged |
| 5 | 29.84 | 77 | 65 | | 9- 3-31 | Washed |

The curve No. 3 was obtained on the 1.125-in. cable after it had been completely polished with steel scratch brushed. This polishing was done by mounting the brushes on one-half horsepower motors which were carried along on the conductor by a frame supported on rubber-tired castors. See Fig. 3. This treatment produced a satin finish, removing all oxides and giving an absolutely clean cable. This surface appeared, when examined under a magnifier, as though it had been hammered with extremely minute hammers. These minute depressions were uniform over the complete cable and were not nearly so deep as the die marks found on many acceptable cables. This treatment, as seen from the curve, produced a very slight decrease in the corona loss.

Curve No. 4 was obtained on the 1.125-in. cable after it had been buffed with cotton buffing wheels and nickel rouge as an abrasive. This treatment produced an extremely high polish on the cable; so that it could be classed as having a roughness factor of unity other than that imposed by the stranding. As can be seen from the curves, this buffed cable had an extremely low loss. Unfortunately, this was not a permanent condition and the aging of this surface is discussed in a later paragraph.

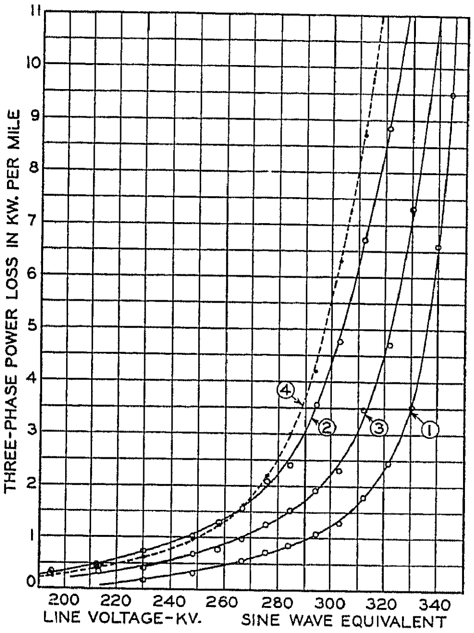

FIG. 6—CORONA LOSS CURVES SHOWING AGING OF BUFFED CABLE

| 1.125-in. cable—22-ft. horizontal spacing | | | | | | |
|---|---|---|---|---|---|---|
| | | Temperature deg. fahr. | | | | |
| Curve No. | Barometer in. hg. | Dry bulb | Wet bulb | Cable | Date | Surface condition |
| 1 | 29.84 | 72 | 55 | 80 | 10- 3-31 | Buffed |
| 2 | 29.95 | 68 | 58.5 | 80 | 10- 5-31 | Buffed |
| 3 | 30.05 | 69 | 59 | 79 | 10-12-31 | Buffed |
| 4 | 29.84 | 77 | 65 | | 9- 3-31 | Washed |

To more nearly simulate the conditions as encountered in field erection, the cable was dragged for one-half mile in the fine crushed rock on a road shoulder. This produced a decided roughening of the surface and carried with it considerable dirt from the road. The cable as erected after this treatment gave a loss as shown by curve No. 5. It was rather surprising to see that this curve fell below the loss curve for the same cable as received from the factory. However, it should be remembered that the grease, die compound or other foreign matter had been completely removed from the conductor before it was dragged; so that this condition may be better than that which would result from a new cable that was dragged in erection. This rough surface also aged rapidly and is discussed in the following paragraph.

*Aging of Surfaces.* In order to have some definite information as to the aging of dragged cables, the 1.125-in. cable was allowed to remain in place for seven months. During this time appreciable aging occurred as is shown in Fig. 5. The aging was uniformly progressive as shown by curves No. 1, 2, 3 and 4, decreasing the loss with time. Curve No. 1 was taken immediately after the cable was dragged. Curve No. 4 shows that the loss has decreased until it is less than that for the washed cable, which is given by the dotted curve, No. 5. A further test taken at the end of the seven months, shows that the loss is practically unchanged. This decrease of corona loss due to aging of the conductor is extremely gratifying and helpful as it eliminates the need for purchasing excess copper or expensive erecting precautions to eliminate the loss resulting from slight roughening.

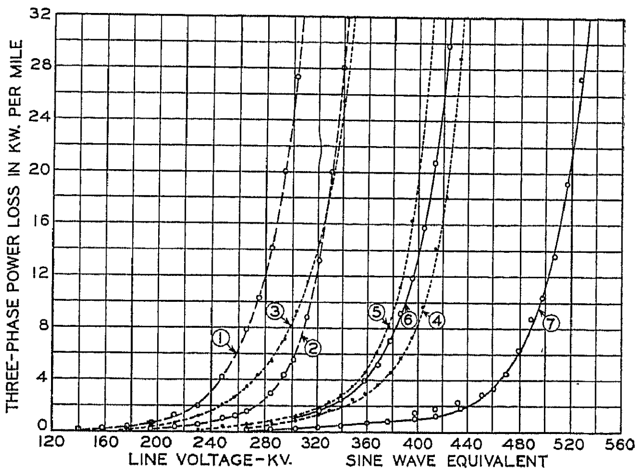

FIG. 7—CORONA LOSS CURVES SHOWING VARIATION OF LOSS WITH DIAMETER

| | | | Temperatures deg. fahr | | | | | |
|---|---|---|---|---|---|---|---|---|
| Curve No. | Cable diameter in in. | Barometer in hg. | Dry bulb | Wet bulb | Cable | Date | Horiz. spacing in ft. | Surface condition |
| 1 | 1.125 | 29.79 | 77 | 66 | | 8-28-31 | 22 | New |
| 2 | 1.125 | 29.84 | 77 | 65 | | 9- 3-31 | 22 | Washed |
| 3 | 1.49 | 30.01 | 68 | 58 | 76 | 10-23-31 | 30 | New |
| 4 | 1.49 | 30.05 | 71 | 53 | 80 | 10-27-31 | 30 | Washed |
| 5 | 1.49 | 29.85 | 80 | 59 | 82 | 10-29-31 | 22 | Washed |
| 6 | 2.0 | 29.93 | 82 | 61 | 93 | 11- 6-31 | 30 | New |
| 7 | 2.0 | 30.05 | 66 | 48 | 80 | 11-12-31 | 30 | Washed |

The aging of the buffed cable was not so uniform in progression as that of the dragged cable. By reference to Fig. 6 it can be seen that the lowest loss as found on the buffed cable is that of curve No. 1, obtained on the day the buffing was completed. Two days later the loss was much higher, as shown by curve No. 2. This curve approaches the loss value as obtained on the washed cable, as given by the dotted curve, No. 4. Nine days after the buffing as shown by curve 3, the loss had decreased to a lower value again, but not so low as that obtained immediately after buffing. The only explanation that can be given for this irregular behavior of the buffed cable is that the surface was more perfect than could be obtained in open air.

From the observations of the various conditions as they effect corona loss, it can be said that the reliable surface to use for the comparison of cables is that of a relatively new, unused cable which has been thoroughly cleaned with gasoline, or some solvent for cutting the the die lubricant, followed by a soap and water cleaning. Some other cleaning methods may give even lower corona loss, but all cables to be compared should be cleaned in the same manner. For this reason the comparison of the different sizes is made on the basis of the washed cable tests.

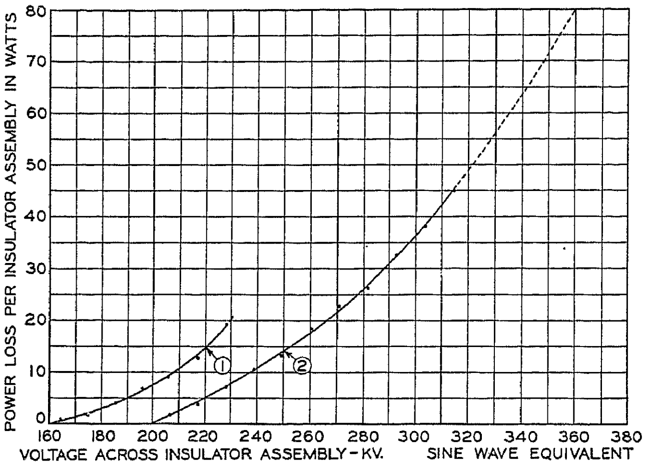

Fig. 8—Loss Curves on Insulator Strings

Curve 1. 18—10-in. sections, 5 in. hanging length. Koontz shield on lower end of string only

Curve 2. 18—10-in. sections, 5 in. hanging length. Aluminum radio shields at each end of string

*Comparison of Size of Cable.* The curves of Fig. 7 show the loss values as obtained on the 1.125-in., 1.49-in. and the 2.0-in. cables. It can be seen from the curves for the washed cables, Nos. 2, 4, 5 and 7 that the voltage shift for the same power loss is practically proportional to the part of $E_0$ which is affected by dimensions; namely, $r \log S/r$, where $E_0$ is the disruptive voltage, $r$, the radius of the conductor and $S$, the spacing. The washing of the 1.125-in. cable shifted the loss so as to allow it to operate with the same loss, 40 kv. higher than the new unwashed cable. By washing the 1.49-in. cable it was shifted approximately 100 kv.; and for the same loss the 2.0-in. cable was shifted approximately 110 kv. higher by washing.

Curve No. 5 of Fig. 7 is the loss curve on the 1.49-in. cable with 22-ft. spacing, and was obtained after the cable was washed and after the loss measurements were obtained with the 30-ft. spacing.

The new unwashed cable tests, curves Nos. 1, 3 and 6, show the 1.125-in. cable better in proportion than the other unwashed cables. This is partially due to the fact that the 1.49-in. cable was rained on slightly before the first loss measurement was obtained. This is known to raise the loss of a new cable the first time that it occurs.[1] Further, the 1.125-in. cable had aged in storage for three years before erection, which could have lowered its loss somewhat.

*Insulator Loss Data.* Curve 1 of Fig. 8 gives the loss on one of the insulator and shield assemblies that was used to support the 1.125-in. conductor. Since the loss was practically zero up to 160 kv. to neutral, no correction for insulator loss was necessary.

Curve No. 2 is the loss curve for the insulator assembly used on the 1.49-in. and the 2.0-in. cables, shown in Fig. 10. From observing this curve it can be seen that the insulator loss is practically zero for voltages to neutral of 200 kv. (346 kv. line). Thus this insulator string showed practically no corona loss over the voltage range where the 1.49-in. cable was tested. However, the low loss range of the 2.0-in. cable covers practically the same range as the loss curve for the insulator string. This correction was applied to all of the data on the 2.0-in. cable equal to the loss on the proper number of insulator assemblies involved.

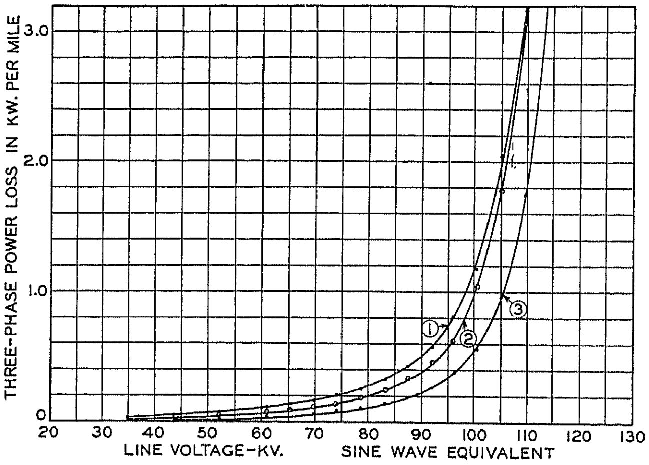

Fig. 9—Corona Loss Curves Showing Effect of Configuration and Transpositions

No. 2 wire—used cable, weathered surface

| | | Temperatures deg. fahr | | | | | |
|---|---|---|---|---|---|---|---|
| Curve No. | Barometer in. hg. | Dry bulb | Wet bulb | Cable | Date | Spacing in ft. | Configuration |
| 1 | 30.07 | 52 | 46 | 55 | 12- 1-31 | 5.05 | Flat |
| 2 | 30.07 | 53.5 | 47 | 57 | 12- 1-31 | 5.05 | Flat Transposed |
| 3 | 29.92 | 54 | 45.5 | 60 | 11-27-31 | 6.3 | Triangular |

*Flat, Triangular, and Flat Transposed Spacings.* It was desired to determine whether there was a change in the loss on lines due to the configuration. A three-phase line of No. 2 wire was erected with a total length of 1,050 ft. The loss was measured on this line for a horizontal spacing of 5.05 ft. and an equivalent triangular spacing of 6.4 ft. The loss curves as obtained for these two conditions were in rather close agreement. The lower loss value, however, was on the triangular spaced condition as seen by curve No. 3 of Fig. 9. Curve No. 1 shows the loss value for the horizontal line. This change in loss is slightly greater than could be attributed to daily variation changes or any change in the surface of the wire due to handling, and appears to be a valid decrease in the loss.

A further attempt to determine the effect of transposing was studied. The line was broken into three equal sections so that there was a complete barrel or a complete transposition section. The loss as determined on this transposed line is given in curve No. 2, and is practically the same as that for the untransposed line, as given in curve No. 1. The very slight difference in the curves could be accounted for by the daily variation as observed on other cables.

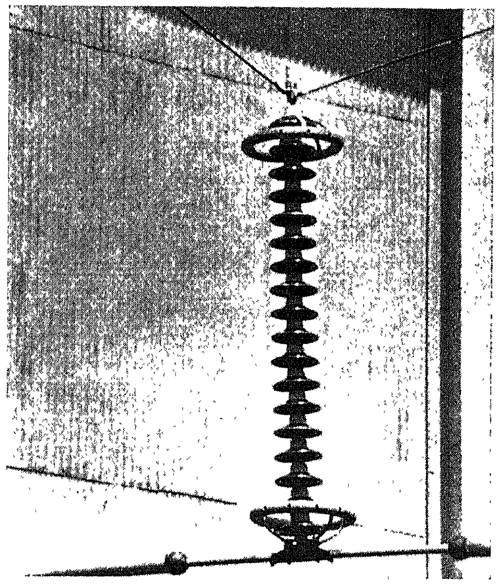

FIG. 10—INSULATOR ASSEMBLY USED ON THE 1.49-IN. AND 2.00-IN. CABLES

## CONCLUSIONS

Further evidence proves that the die grease and other foreign matter, existing on cables as received from the manufacturers, greatly increases the corona loss, and that this loss can be partially eliminated by washing the cable with a solvent, soap solution and thoroughly rinsing in water.

The cleaning of the cable surface by scratch brushing only slightly lowers the corona loss below that which exists on a new cable properly washed.

The polishing of a cable surface by buffing temporarily decreases the loss on the cable below that which exists on a new cable properly washed.

Dragging a clean cable a distance of one-half mile increases the loss on the cable above that which is found on a washed cable, but the loss is less for this condition than for the new, unwashed cable as received from the factory.

The surface of clean washed cables, that have been subsequently dragged, ages rapidly; so that with a year of weathering the loss is practically the same as found on a new, washed, undamaged cable.

The surface produced by buffing ages rapidly, and as observed over one week's time, showed a great variation in loss which was not regular but at times approached the loss value as found for the new, washed cable.

The variation in corona loss as found on new, washed cables shows that the voltage shift for the same power loss on cables of different sizes is practically proportional to $r \log S/r$, which is the factor in $E_0$ which is varied by dimensions.

Insulator loss, if not considered, may introduce an appreciable error in corona loss measurements at high voltages. The loss can be partially eliminated by properly shielding the insulator strings.

A completely transposed line 1,050 ft. long showed the same corona loss as the same length of line untransposed. A horizontally spaced line showed a slightly higher loss than the same length of line with the equivaent triangular spacing.

## ACKNOWLEDGMENTS

Two of the conductor specimens used in the tests reported in this paper were donated to the Harris J. Ryan Laboratory about three years ago.

The 1.125-in. hollow copper cable was donated by the Anaconda Wire and Cable Co.

The 2.0-in. hollow aluminum cable was donated by The Aluminum Company of America.

The obtaining of these data was greatly facilitated by the help of graduate students who showed their interest in the work by their willingness to help whenever needed.

# Appendix

## DESCRIPTION OF CONDUCTORS

All of the cables used in the test were new unused cables on the original reels which came from the factory. The No. 2 wire used in the transposition test was hard drawn, copper wire.

The 1.125-in. diameter cable was hollow copper of the I-beam type construction. This was a single-layer cable with 24 strands in the one layer. The strand diameter was 0.125 in. The diameter of the supporting twisted I-beam core was 0.875 in.

The 1.49-in. diameter cable was a double-layer, hollow-core, copper cable of the I-beam type construction. The diameter of the strands in both layers was 0.0971 in. The diameter of the supporting twisted I-beam core was 1.100 in. The inner layer contained 37 strands and the outer layer contained 43 strands.

The 2.0-in. diameter hollow aluminum cable was a single-layer cable, with the strands supported by a flexible-tube center. The outside diameter of this flexible tube was 1,636 in. The outside layer of the cable was of 30 strands of aluminum with a strand diameter of 0.182 in.

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## Discussion

**Wm. S. Peterson:** In applying the results of these very accurate measurements of corona loss to the actual design of a line, we find that the conditions along the line, such as altitude, temperature and other conditions, are not the same as those at the laboratory, where the investigations had to be made. In the laboratory each variable must in general be investigated separately, and then these effects must be united by some statement of physical law connecting them. From this a more nearly correct estimate can be made for actual line conditions.

The economically important part of a corona loss curve is the region of lower losses. It will be recalled that the early work of Mr. F. W. Peek on this subject gave us a formula that was more applicable to the upper part of the corona loss curve.' Our need for some method of calculating corona loss for the lower value of losses, as well as the higher values, leads to the development of a theoretical formula modified by empirical correction that should be of interest to engineers dealing with corona. Due to lack of space, the mathematical derivations and experimental corrections will not be given in detail. Only the results and method will be described.

*Loss Formula.* The corona loss was considered to be the loss due to charging current flowing radially through the corona envelope. The drop in voltage through the envelope was assumed as being the integral of the potential gradient from the point where the gradient in air exceeded 53.6 kv per inch effective values, to a point on the conductor at some higher value. Instantaneous values of current and voltage were used. For the portions of the cycle where the voltage is too low to cause air breakdown, no loss was assumed to occur. It is realized that this theory is rather crude. Much dependence is placed on the further empirical corrections.

As a result of this theory the following formula was evolved:

$$P_c = \frac{0.0000337 fE_n^2}{(\log_{10} s/r_1)^2} \left[4.606 \log (E_n/E_0) - 1 + (E_0/E_n)^2\right]$$

Where $P_c$ is the corona loss in kilowatts per mile per conductor, $f$ is the frequency, $s$ is the equivalent conductor spacing in inches, $r_1$ is the radius of the conductor in inches, $E_n$ is the voltage to neutral in kv, and $E_0$ is the disruptive voltage in kv at which the voltage gradient at the surface of the conductor is equal to the air breakdown value.

The importance of the above equation is that it leads to the suggestion that from actual tests an empirical curve might be determined that would replace the terms in the brackets, if they should not give a curve that accurately fits the test data. In other words, the empirical modification of the theoretical formula would be a curve derived from tests that would be a function of the ratio $E_n/E_0$ and would be the same for all cables and conditions.

Examination of corona test data indicated that the theoretical formula gave quite close results for voltage ratios in the vicinity of 1.3. However it did not fit the curves as closely as desired for the entire range of voltage.

Plotting of the results of a great many corona loss curves, taken by many investigators over a wide range of conditions revealed that the empirical modification suggested above could be made and be in agreement with over 90 per cent of the curves.

Corona loss is then given by

$$P_c = \frac{0.0000337 fE_n^2}{(\log_{10} s/r_1)^2} (\phi_c')$$

where $\phi_c'$ is a value taken from the accompanying curve Fig. 1, and is a function of the ratio $E_n/E_0$, and is spoken of as an empirical corona loss function.

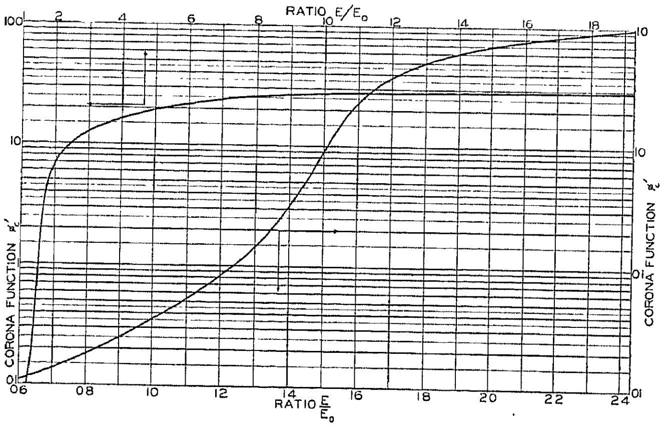

Fig. 1—Empirical Corona Loss Function for Calculating Purposes

It will be noted in the formula that the loss is considered to vary directly as the frequency. This is the theoretical result. It also agrees quite closely with some of Mr. Peeks early work, where his experiments indicated the loss would vary directly with the frequency. It is not the intention of this discussion to maintain that the corona loss with direct current will be zero. For commercial frequencies, 25 cycles and above, it is believed that good accuracy will be obtained by using the value in the formula.

*Disruptive Voltage.* For smooth round conductors, the value of $E_0$ as calculated by Mr. Peek's formula was used, with a slight modification for air density, which will be discussed later.

$$E_0 = 123.4\, m\, \delta^{2/3}\, r \log_{10} s/r. \text{ (kv to neutral)}$$

where $m$ is a roughness factor; $\delta$ is the air density factor and is equal to [17.9 by barometer inches/(459 + fahrenheit degrees)]; $r$ is the radius of the conductor and $s$ is the equivalent spacing, both in the same units.

For stranded conductors it was considered desirable to attempt to develop a new formula that would take account of the stranding so that the factor $m$ would not have to be used for that purpose, and thus leave $m$ to take care of the individual strand conditions.

Omitting the development, the formula for $E_0$ for cables with 12 or more strands in the outside layer is as follows:

$$E_0 = \frac{123.4\ \delta^{2/3}\ m\ [\log\ (s/cr_i) + (n-1)\log 2s/(d-2cr_i)]}{1/cr_i + (n-1)/(d-2cr_i)}$$

(kv to neutral)

where all log terms are to the base 10, $r_i$ is the radius of an individual strand; $n$ is the number of strands in the outside layer of the cable, and $c$ is a quantity given by

$$c = \left[\ 1 - \frac{\sin\ (\pi/2 + \pi/n)}{\pi/2 + \pi/n}\ \right]$$

Certain simplifying assumptions were made in the development of the above formula so that it is not accurate for a small number of outside strands. For the special case of cables with six outside strands, the following formula was developed.

$$E_0 = \frac{123.4\ \delta^{2/3}\ rm\ [\log s/r + 0.0677]}{1.37}\ \text{(kv to neutral)}$$

*Air Density Factor.* Recently at the Ryan High Voltage Laboratory at Stanford University, Mr. Victor Siegfried conducted some corona tests dealing with a conductor in a tank, in which the atmospheric conditions could be controlled. These tests provided data on the effect of pressure, temperature and humidity.[1] Also at the same place, Mr. Alexander Nuttall conducted some corona tests in which the temperature of the conductor was varied through a wide range.[2] A study of their results revealed that the most practical variation of $E_0$ to use, as the air density was varied, was as $\delta^{2/3}$. On the basis of these tests and further verification from general corona tests, by various investigators, it was decided to use this value in the calculations of $E_0$ that have been given. It was also concluded that the temperature of the conductor should be used rather than the temperature of the air.

*Roughness or Condition Factor.* The roughness factor $m$ has been simplified in that it is related to the condition of the individual strands, however it has been found it must also take account of whether the conductor has been weathered, or washed, or is in the condition represented by new unwashed cables, which have been discussed by Mr. Carroll and Mr. Cozzens. The effect of humidity on its value has not as yet been entirely determined.

Most of the tests run by Mr. Carroll and Mr. Cozzens were in the afternoon when humidity was low. It was a time of day when corona losses were probably at their minimum values.

For new unwashed cables in these tests, the value of $m$ as used in the foregoing formulas ranges from 0.67 to 0.74. After washing, the range for all sizes of cable tested was very narrow varying from 0.912 to 0.93. By scratch brushing the value of $m$ was reduced to 0.885. By buffing the value of $m$ was raised to an average of 1.00. The dragged and dusty cable had a value of $m$ of 0.72 to 0.75. As this cable was weathered it gradually improved until after five months it attained a value of $m$ of 0.945.

For general purposes it is felt that the proper value of $m$ to use with low humidity and with the wire well weathered or in good clean condition is approximately 0.92. During the night with low humidity this value may go as low as 0.78. A general value that was used for comparison with test data, where the conditions were not known exactly, was 0.90. This gave very good results. For general line design a value of $m$ between 0.87 and 0.90 is probably correct.

It is anticipated that as further information becomes available on corona loss, the wide range of conditions that have to be taken care of by the condition (roughness) factor $m$ will be reduced and that formulas will become available to account accurately for many conditions that are not well understood at the present time. It is also probable that a greater number of accurate experiments under controlled conditions will furnish data whereby the curve giving the corona loss function may be more accurately determined.

At the present state of knowledge concerning corona, the method of predetermination of corona loss outlined in this discussion has served quite well to give accurate curves for practical engineering purposes. Excellent agreement with a great variety of tests has been obtained.

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[1] "The Effect of Atmospheric Conditions on Corona Loss." (Thesis)

[2] "The Effect of Conductor Temperature and Various Surface Conditions on Power Loss Due to Corona on Conductors at High Voltage." (Thesis)

# The Triple-Harmonic Equivalent Circuit in Three-Phase Power Transformer Banks

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***Synopsis.***—*The importance of triple-harmonic voltages and currents in electrical power systems is generally recognized by engineers associated with the power and telephone industries. It is desirable to have some convenient method of representation and calculation of the triple-frequency effects in three-phase power systems.*

*The path of the third-harmonic current is different from that of the fundamental current and for this reason the circuit can be considered as separate and distinct. The characteristics of the triple-frequency circuit as determined by laboratory experiment are given in this paper. Methods of measurement of the required quantities for accurate solution of the triple-frequency circuit are described. The results of an experimental investigation of the equivalent triple-frequency circuit as proposed by H. S. Osborne in 1915 are set forth. A typical simple three-phase power network has been set up and the measured currents compared with computed values. Oscillograms are presented of voltages and currents with typical transformer connections demonstrating the principles of operation of the circuit both for normal and abnormal excitation conditions. The effects of various types of connected loads are discussed, with particular attention given to the condition of triple-frequency resonance. It is shown that triple-frequency resonance occurs when the external capacitive reactance of the circuit is equal to the triple-frequency no-load impedance of the transformer. Resonance produces large triple-frequency currents and serious distortion of the line-to-neutral voltage of the system.*

* * * * *

## INTRODUCTION

THE lack of symmetry existing between the curves of instantaneous voltage applied to a transformer and the resulting exciting current was first demonstrated by Harris J. Ryan in 1889[1], and since that time much has been written on the subject from different view points. The importance of a clear understanding of the action of harmonic currents arising from the varying permeability of transformer steel cores in polyphase circuits is universally recognized. Because of a number of undesirable effects resulting from the behavior of triple-frequency voltages and currents in present day power transmission and distribution systems, it has become of considerable importance to the power and telephone industries to be able to predict, with a fair degree of accuracy, the value of these triple-frequency quantities in a particular system, with a view to their proper control. In the past only rough approximations have been used for estimating the amount of harmonic current which would result from various transformer connections on power systems. It was believed that it would be possible to calculate accurately in a simple manner the value of such currents if sufficient information were available. Working on this assumption, transformer and other circuit constants were carefully determined in the laboratory, then these transformers were connected in a manner similar to that used in practise and the harmonic currents in the circuit measured. These measured values were compared with values obtained by analytical calculation.

The path of the triple-frequency current and all multiples of the third-harmonic current is different from that of the fundamental current so that the circuit actually becomes a separate and distinct one. This paper will be devoted mainly to a brief discussion of this circuit which will be termed "the triple-harmonic circuit." An experimental proof of its equivalent representation is presented with suggestions as to its use, behavior and limitations.

## PRODUCTION OF HARMONIC CURRENTS

The well-known fact that when a true sinusoidal voltage is applied to a transformer the resulting exciting current is not sinusoidal is shown in Fig. 1. Upon analysis it is found that this exciting current contains harmonics of 3rd, 5th, 7th, etc., order (the amount of the harmonic component decreasing as the frequency increases). It is a well established fact that the distortion of the current wave results from the varying permeability of the transformer steel core. It also must be admitted that any harmonic component of current can exist only as the result of a corresponding harmonic of e.m.f. in the circuit. In the oscillogram shown, the wave form of the generator supplying the voltage to the transformer was almost perfectly sinusoidal. The resulting conclusion must be that the transformer itself, due to the action of its

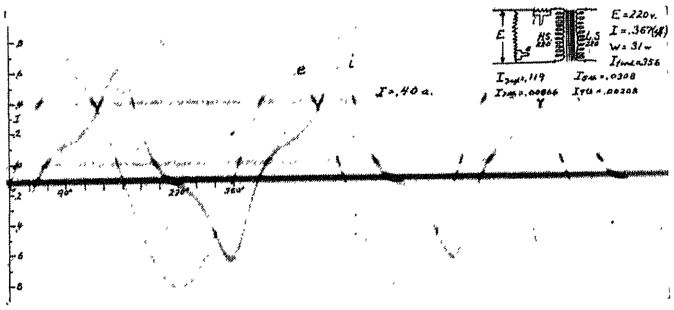

FIG. 1—THE APPLIED VOLTAGE AND EXCITING CURRENT FOR A 3-KVA. TRANSFORMER

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1. For references see Bibliography.

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steel core, produces the various harmonic components of voltage which cause the harmonics of current present in the transformer exciting current.

The above fact is made evident by the suppression of any frequency of harmonic current. For example, by using similar transformers with a star connection on the primary with isolated neutral the triple harmonic currents are all in phase when considered acting in the direction toward the neutral, (*i. e.*, they are 3 × 120 deg. = 360 deg. apart, or in phase toward the neutral) and consequently are suppressed. In this case the transformer generated triple e.m.f. appears in the total wave of voltage across the terminals of a single transformer. Such triples of voltage will appear in all windings of the transformer if no connections exist except this primary one. If now the secondary windings be delta-connected the triple voltages in each winding will be added directly in phase in the circuit around the delta. This means that before closing the delta there will exist across its open ends a triple harmonic of voltage which is three times the triple voltage of each transformer secondary coil. Upon closing the delta this voltage is short-circuited through the three no-load triple-frequency transformer impedances of the secondary windings in series. A corresponding triple-frequency current flows around the delta. Whenever this current is permitted to flow it has a direct demagnetizing effect upon the flux which produces its e.m.f. because it lags this e.m.f. by 90 elec. deg. The action is similar to the demagnetizing effect in a polyphase alternator under short-circuit conditions where the armature current is mainly limited by the demagnetizing effect of armature reaction.

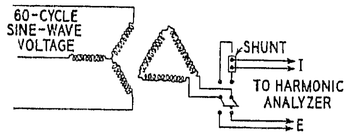

Fig. 2—Circuit for Measuring the Triple-Frequency No-Load Impedance of a Transformer

In the transformer, the triple harmonic of current may exist in any winding in which the connections give a path permitting it flow. It is also common to have it divided among the windings with a part flowing in each. This of course depends upon the transformer connections.

## Transformer Impedance Measurements

If computations of triple harmonic currents are to be accurately made it is necessary to have complete information regarding: (a) the triple-frequency voltage generated in a transformer with the triple harmonic of current suppressed, (b) the transformer impedance to this current and, (c) the leakage impedance of the different windings.

All values obtained were reduced to the common basis of 220 volts which was used for all cases.

*Generated Voltage.* Measurements of the generated triple-frequency voltage in a transformer were obtained by connecting a bank of three similar transformers star-delta as shown in Fig. 2 with one corner of the delta left open and the open ends connected to a high resistance circuit of a harmonic analyzer.

This was obtained by throwing the double-pole switch of the figure in the down position. A true sinusoidal fundamental voltage wave was applied to the transformer bank primary. The secondary triple voltage was measured for different values of applied voltage and a curve drawn as shown in Fig. 3. The generated voltage per transformer is one-third the total voltage measured.

*No-Load Impedance.* By closing the delta through a low resistance shunt, (*i. e.*, by closing the switch in the up position), readings of the triple current could also be obtained on the analyzer. The ratio of triple-frequency voltage per transformer to the triple-frequency current circulating in the closed delta gives the transformer total impedance to this current at the saturation of the core determined by the fundamental applied voltage. These values are shown by the "no-load impedance" curve on the diagram. The effect of the leakage impedance of the winding was not considered in this measurement because of its insignificance in comparison with the quantity measured.

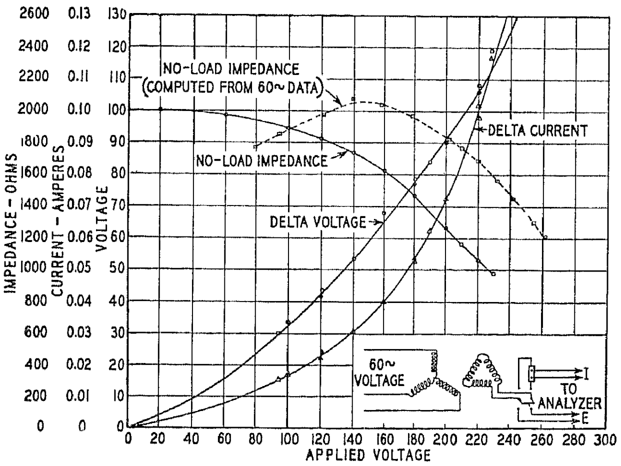

Fig. 3—Third-Harmonic No-Load Impedance of 3-Kva. Transformer

(All values per phase and referred to 220-volt base)

Oscillograms of the open-circuit delta voltage and closed-circuit delta current were taken, with each oscillogram record containing a fixed triple-frequency reference wave. From these oscillograms the phase angle of the no-load impedance was obtained for rated transformer voltage.

In order to ascertain if sufficiently accurate values of the triple-frequency no-load impedance could also be determined from fundamental frequency measurements, the no-load 60-cycle impedance of a single transformer was determined in the conventional manner by the application of a fundamental sinusoidal voltage to the single transformer winding and measurements taken of current and power. The 60-cycle reactance thus measured was changed to a 180-cycle reactance and the impedance plotted as shown on the diagram. The inaccuracy of this latter method is clearly evident.

*Leakage Impedance.* The leakage impedance of each transformer winding was measured by means of a method described by O. G. C. Dahl.[15,19] The harmonic analyzer was used as the most convenient method of accurately obtaining the required measurements. The variation of the 180-cycle leakage impedance of one winding of a transformer as a function of applied voltage is shown in Fig. 4. The leakage impedance decreases with increased transformer voltage due to decreased permeability of the core as saturation increases.

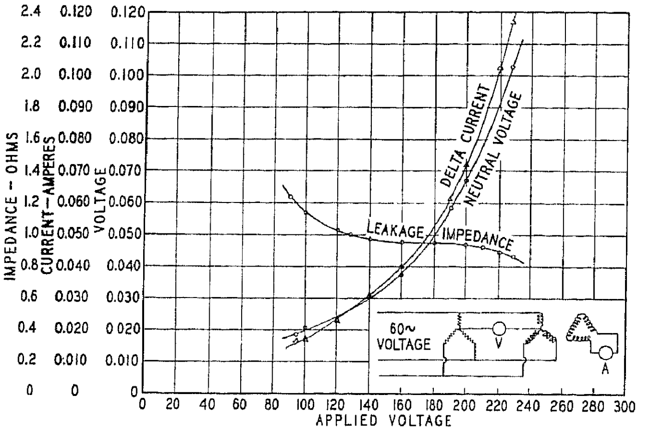

FIG. 4—THIRD-HARMONIC LEAKAGE IMPEDANCE OF 110-VOLT WINDING OF THE 3-KVA. TRANSFORMER

(All values per phase and referred to 220-volt base)

The leakage impedance was also determined by the conventional short-circuit (zero saturation) test at fundamental frequency. It was found that values obtained in this way were considerably in error when compared with those for normal saturation as obtained above.

## THE EQUIVALENT CIRCUIT

In order to determine in three-phase power systems the magnitude and distribution of the third harmonic components of the exciting currents it is desirable to have some convenient method of calculation. The conventional transformer equivalent circuit has been found to be most accurate and convenient for calculating currents and voltages at fundamental frequency. An adaptation of this circuit for application to triple-frequency components of transformer exciting currents was made by H. S. Osborne in 1915.[8] This circuit provides a simple and convenient method of representation of the action of the triple-frequency effects. However, no proof could be found that its accuracy had been established, and it was felt that laboratory measurements showing the integrity of calculation by its use would be of real value.

The representation of the equivalent triple-frequency circuit for a transformer as given by Mr. Osborne, is shown in Fig. 5. This is a T-network similar to the general transformer circuit except for the addition of the generator. The shunt leg consists of a third harmonic generator in series with the no-load impedance. The voltage of this fictitious generator is the triple-frequency component of e.m.f. which exists in the terminal voltage of a single transformer when the third harmonic component of exciting current is entirely suppressed. The no-load impedance is the ratio of the triple-frequency voltage to the current of the same frequency which would flow as part of the exciting current considering no external impedance in the circuit.

The resistance and leakage reactance marked with the subscript *p* represent values of the primary winding while those marked by *s* refer to the secondary coil. The no-load values are marked *nl*. The e.m.f. of the third harmonic generator is designated by *E*.

It will be noted that in this equivalent circuit the amount of the triple-frequency current is mainly determined by the value of the generated e.m.f. and no-load impedance, while its division between the primary and secondary circuits may be largely determined by their relative values of leakage impedance.

In the equivalent circuit different transformer connections may be represented as follows:

If the primary were connected star with no neutral connection, the line *b* would be open and so no third harmonic of current could flow in it, but if a neutral connection is provided, the points *a* and *b* will be closed through an impedance. The type of impedance will depend upon the power source.

If the primary winding were connected delta, the points *a* and *b* would be short-circuited through the leakage impedance furnishing a closed path for the third harmonic current. Similarly, if the secondary winding were a closed delta the points *c* and *d* would be short-circuited. Should the delta be closed through an impedance of any kind, this would be inserted between the points *c* and *d*. It is evident from the equivalent circuit that if both primary and secondary windings were connected delta the third harmonic of current would divide between them inversely as their respective leakage impedances.

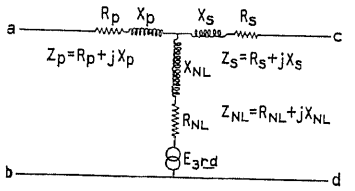

FIG. 5—THIRD-HARMONIC EQUIVALENT CIRCUIT

With the secondary star-connected the method of representation would be similar to that for the same primary connection. Should the load be connected from line to neutral it would also be represented between the terminals *c* and *d*. If the line capacitance is appreciable it will furnish a path for the triple-frequency currents when the neutral is grounded, and therefore would be considered as a capacitance load between the points *c* and *d*.

From the above discussion, it is evident that this equivalent circuit is applicable to all connections where third harmonic currents flow due to the inherent characteristics of the transformers.

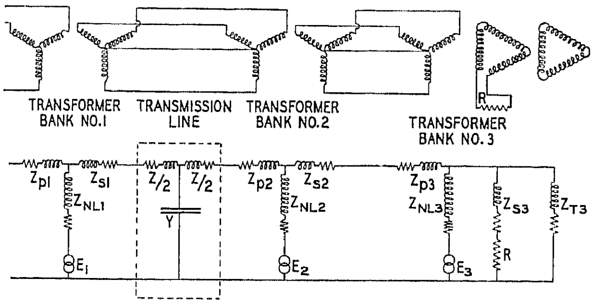

FIG. 6—EQUIVALENT REPRESENTATION OF A TRANSMISSION SYSTEM

The manner in which the equivalent circuit may be applied to various transformer connections on a power system is shown in Fig. 6.

## EQUIVALENT CIRCUIT TESTS AND RESULTS

In order to test the validity of the third-harmonic equivalent circuit, a series of measurements was taken on a typical power-system network. These measurements were then compared with the computed values obtained from a solution of the equivalent circuit representing the network. Since it was impracticable in this investigation to conduct tests on an actual power transmission system, laboratory apparatus was set up in the electrical machinery laboratory at Stanford University to represent practical conditions.

The network used in this test is shown diagrammatically in Fig. 7. Power was supplied by a 52-kw. sine-wave alternator directly coupled to a synchronous motor. Normal 60-cycle sinusoidal voltage was applied to the primary of a star-star bank of 3-kva. transformers. This bank in turn supplied a bank of 2-kva. transformers which was connected star-delta, the neutral being connected to the secondary neutral of the first bank of transformers. The bank of transformers connected to the incoming power lines was used for the purpose of obtaining a fixed reference wave for the oscillograms. The third-harmonic neutral current circulating between the transformers and the synchronous motor was recorded at the top of all oscillograms for reference purposes.

Various types of impedance were placed in the corner of the delta circuit of the 2-kva. transformers, to determine the effect of different loads on the triple-frequency circuit under actual operating conditions. With this connection it should be noted that a particular value of impedance inserted in the corner of the delta will have the same effect upon the third-harmonic component of the transformer exciting current as the same impedance connected as a balanced three-phase load on any star-connected winding of the transformer bank with neutral connection. For example, an impedance of some value $Z$ inserted in the corner of the delta connection corresponds to an impedance $Z/3$ per phase on the star-connected primary winding assuming one-to-one transformation ratio.

Known values of resistance, inductance, and capacitance were inserted separately in the corner of the delta winding, and for each case the third-harmonic currents in the neutral and in the delta were measured on a harmonic analyzer. The analyzer readings were checked by a thermocouple ammeter, and in most cases the two agreed very closely, showing that the currents were almost entirely third-harmonic or 180-cycle. This was also verified by oscillograms of the neutral and delta currents.

For each case in which measurements were taken, the neutral and delta currents were computed by means of the equivalent circuit, Fig. 7. Having previously determined the 180-cycle voltages generated in the transformers and the no-load impedances and treating leakage impedance as negligible, it is necessary only to include the value of external impedance for $Z_3$ in order to solve the circuit. The equations for its solution are given in Table I. Their derivation is quite simple and will not be given here.

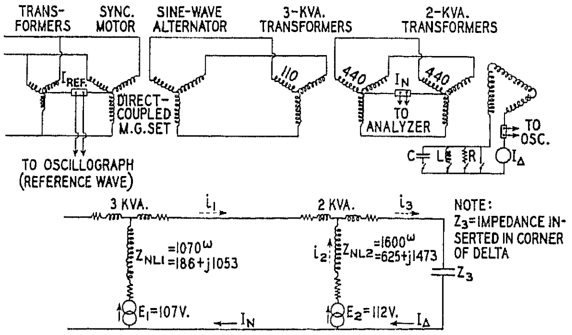

FIG. 7—TEST CIRCUIT AND ITS EQUIVALENT CIRCUIT

The results obtained from the series of tests are shown in Table I. The values computed by the equivalent circuit method agree very well with the measured values. In nearly all cases the agreement is within 5 per cent, which may be considered accurate enough for most purposes. It will be noted that for the cases of low external impedance, the error is small and that as the impedance is increased the disagreement somewhat increases. For the case of high capacitive reactance, which is nearly equal to the no-load impedance of the transformer, the error is 50 per cent.

These errors are due almost entirely to differences in saturation as a result of triple-frequency current changes

TABLE I—TABULATED RESULTS—EQUIVALENT CIRCUIT TEST

(See Fig. 7) $Z_1 = 186 + j1053$
$Z_2 = 625 + j1473$

| External impedance per transformer ($Z_3/3$) | | Delta current $I\Delta$ amperes | | | Neutral current (per transformer) $I_n$ amperes | | |
|---|---|---|---|---|---|---|---|
| Type | Value | Measured | Computed | % diff. | Measured | Computed | % diff. |
| Short | Zero | 0.170 | 0.169 | − 0.6 | 0.102 | 0.100 | − 2.0 |
| Short | Zero | 0.172 | 0.169 | − 0.6 | 0.103 | 0.100 | − 2.9 |
| Res. | 151 + j0 | 0.155 | 0.156 | + 0.6 | 0.0913 | 0.0922 | + 1.0 |
| Res. | 182 + j0 | 0.150 | 0.152 | + 1.3 | 0.0900 | 0.0901 | + 0.1 |
| Res. | 306 + j0 | 0.133 | 0.139 | + 4.5 | 0.0800 | 0.0822 | + 2.8 |
| Res. | 307 + j0 | 0.132 | 0.139 | + 5.3 | 0.0800 | 0.0822 | + 2.8 |
| Ind. | 0 + j 161 | 0.141 | 0.136 | − 3.5 | 0.0840 | 0.0802 | − 4.5 |
| Cap. | 0 − j 36.3 | 0.182 | 0.178 | − 2.2 | 0.108 | 0.106 | − 1.9 |
| Cap. | 0 − j 269 | 0.280 | 0.278 | − 0.7 | 0.167 | 0.166 | − 0.6 |
| Cap. | 0 − j1062 | 0.460 | 0.231 | −49.8 | 0.282 | 0.141 | −50.0 |

Equations
(For Circuit See Fig. 7)

$$I_1Z_1 - I_2Z_2 = E_1 - E_2 \tag{1}$$

$$I_1 + I_2 = I_3 \tag{2}$$

$$I_1 = \frac{E_1\,(Z_2 + Z_3) - E_2Z_3}{Z_1Z_2 + Z_2Z_3 + Z_1Z_3} = I_n$$

$$I_3 = \frac{E_1Z_2 + E_2Z_1}{Z_1Z_2 + Z_2Z_3 + Z_1Z_3} = I_\Delta$$

$$I_3Z_3 = V \tag{3}$$

$$I_1Z_1 + V = E_1 \tag{4}$$

$$I_2 = \frac{E_2\,(Z_1 + Z_3) - E_1Z_3}{Z_1Z_2 + Z_2Z_3 + Z_1Z_3}$$

$$V = \frac{Z_3\,(E_1Z_2 + E_2Z_1)}{Z_1Z_2 + Z_2Z_3 + Z_1Z_3}$$

both in magnitude and phase angle. A small change in the saturation of the steel core causes variation in the transformer constants, resulting in errors in the computed values. It is also possible that an error exists as a result of assuming the generated voltages $E_1$ and $E_2$ of Fig. 7 to be in exact phase. A difference in the degree of core saturation in transformers of the two banks might be responsible for a phase difference between them.

## EFFECTS OF RESISTANCE, INDUCTANCE, AND CAPACITANCE IN THIRD-HARMONIC CIRCUIT

A large number of oscillograms was taken for the purpose of recording phase relationships and wave distortion for different conditions of loading of the third-harmonic circuit. When a comparison of records is made for two conditions of loading, any change in phase angle is determined by comparing the position of the two waves with respect to the fixed reference wave appearing at the top of each record.

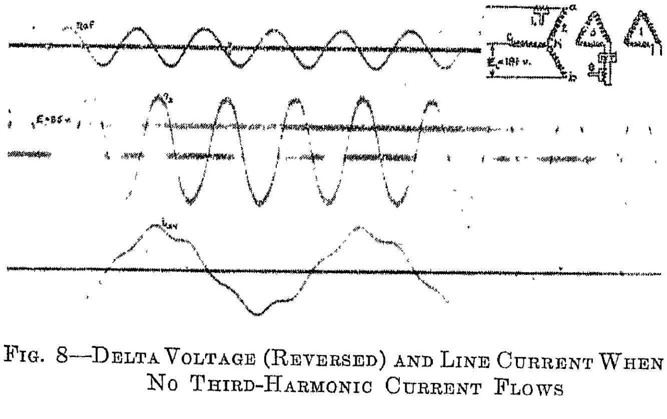
FIG. 8—DELTA VOLTAGE (REVERSED) AND LINE CURRENT WHEN NO THIRD-HARMONIC CURRENT FLOWS

It should be noted here that all oscillographic records of voltage were made with the aid of an inverted vacuum tube.[20] The inverted vacuum tube draws no current from the circuit to which it is connected, and consequently does not disturb conditions in that circuit.

When the third-harmonic component of exciting current is suppressed a third harmonic of flux is produced within the steel core of the transformer. This flux causes the triple-frequency voltage shown in Fig. 8. In this oscillogram the voltage is reversed due to the inverted vacuum tube connection. Distortion in the phase voltage of each transformer winding resulting from the suppression of the third-harmonic current, is shown in Fig. 9.

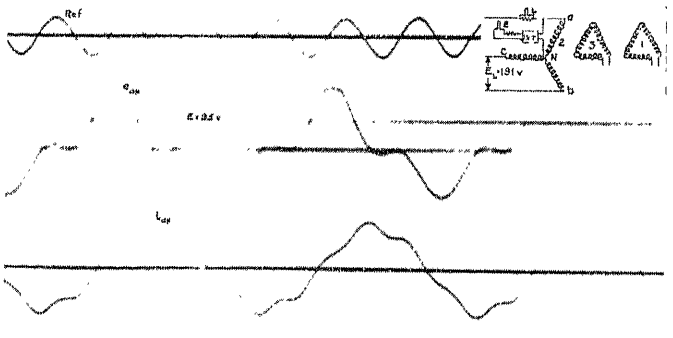
FIG. 9—LINE-TO-NEUTRAL VOLTAGE AND LINE CURRENT WHEN NO THIRD-HARMONIC CURRENT FLOWS

If the normal third-harmonic current, Fig. 10, is allowed to flow, normal excitation results and the phase voltage wave shape is identical with that of the applied voltage as shown in Fig. 11. For this condition the third-harmonic component of current (which is required by the core to produce a sine-wave of flux) flows in the delta circuit, and therefore a sine-wave of voltage appears across the winding of the transformer.

If additional resistance now be inserted in the delta circuit it is to be expected that the triple-frequency current will shift ahead in time phase with respect to its original position and will, at the same time, decrease in magnitude. This assumption, which results from an analysis of the equivalent circuit, is verified by an oscillogram taken for this particular case, Fig. 12. This shift in phase and decrease of the current means that the current is no longer in the proper position or of sufficient magnitude to cause a sine-wave of flux to exist in the core. Hence a resultant third-harmonic flux will exist, giving rise to a third-harmonic voltage across each phase.

Should an inductance be inserted in the corner of the delta in place of the resistance, the phase shift of the current will be in the opposite direction, or behind in time phase, due to the increase of the inductive reactance component of the impedance of the complete circuit, Fig. 13. This effect is not pronounced since the resistance component of the no-load impedance is comparatively small. The current will decrease from its normal value and will, as before, cause a resultant third-harmonic voltage to appear in the transformer voltage wave as a result of the distorted flux wave.

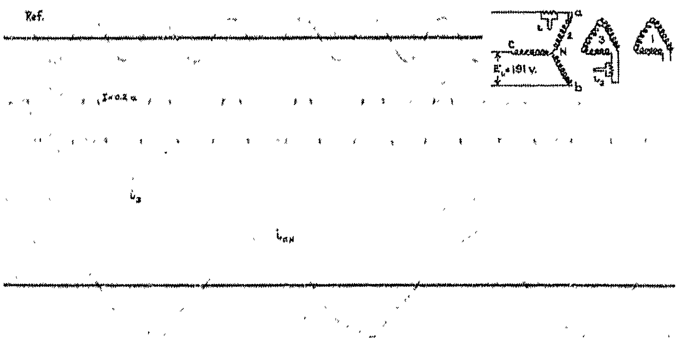

FIG. 10—DELTA CURRENT AND LINE CURRENT WITH NO EXTERNAL IMPEDANCE

When a capacitance is placed in the delta circuit an opposite condition from that of the inductance is encountered. Instead of increasing the total impedance of the circuit, the effect of the capacitance is to decrease it. It is evident that a small value of capacitive reactance in the delta will cause the third-harmonic current to be larger in magnitude than the normal value. The current will shift ahead in time phase from the normal position, Fig. 14. There are now two factors contributing to the distortion of the flux wave; first, the shift in phase position, and second, the increase in magnitude of the current above the normal value required for a sine-wave of flux. The latter effect causes a direct magnetizing force upon the core, and the flux caused by this current now magnetizes the core in such a manner as to produce a third-harmonic flux in the same direction as that flux which the core generates when the third-harmonic current is suppressed. Consequently, the third-harmonic voltage generated by this resultant flux will be larger in value and will cause a greater distortion in the total voltage wave across the winding. This is clearly shown in Fig. 15.

### THIRD-HARMONIC RESONANCE

From the above oscillograms and a study of the equivalent circuit, it is apparent that a capacitance in the delta circuit giving a corresponding value of capacitive reactance equal to the no-load inductive reactance of the transformer will cause a condition of resonance when the current will be limited only by the equivalent resistance of the circuit. Fig. 14 is an oscillogram of the delta current and line current when the above resonance conditions were approached. Note the large distortion of both currents.

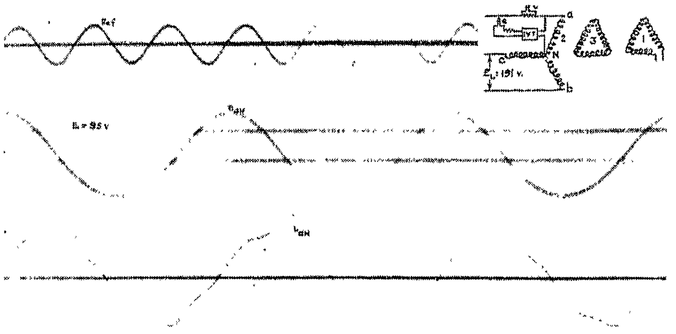

FIG. 11—LINE-TO-NEUTRAL VOLTAGE AND LINE CURRENT WHEN ONE DELTA IS CLOSED

In order to determine this condition of resonance experimentally, a series of readings of delta current was taken as the value of capacitance was varied over a wide range. From these readings, a curve was plotted showing third-harmonic current as a function of capacitance. The resulting curve is shown in full line in Fig. 16. The shape of the curve indicates that a condition of resonance actually does exist, and that for a certain value of capacitance the current rises sharply to a high value. For the resonance condition the distortion of the flux will be a maximum, and the saturation of the steel core at triple-frequency will be extremely high. Fig. 15

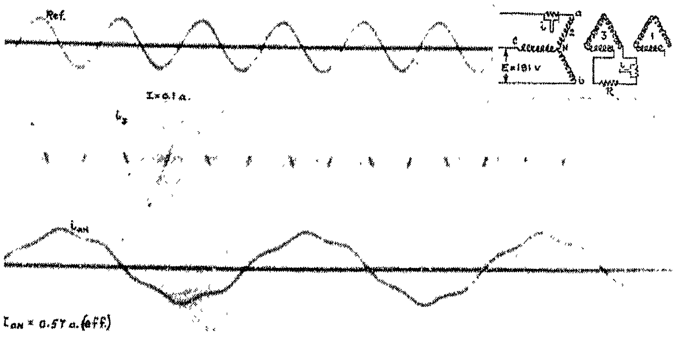

FIG. 12—DELTA CURRENT AND LINE CURRENT FOR A RESISTANCE LOAD OF 2,461 OHMS IN THE DELTA CIRCUIT

shows the large distortion in the transformer voltage when resonance is approached.

Assuming the normal no-load impedance of the transformer to remain constant, a theoretical resonance curve was computed over the range covered by the experimental curve and plotted in Fig. 16. Agreement in the two curves is not obtained near or at the point of resonance. Computation on the basis of the equivalent circuit does not take into consideration the change in saturation which actually occurs under these abnormal conditions which accounts for the lack of agreement between the two curves. The experimental curve indicates a lower no-load reactance than does the theoretical curve. This may be attributed to an increase of saturation of the transformer core by the triple-frequency flux.

## APPLICATIONS

When the necessity arises for making an investigation of the triple-frequency harmonics in a power system network, a simple and yet accurate solution of the circuits involved is highly desirable. From the results of this investigation, it appears that the triple-frequency equivalent circuit will serve this purpose in a satisfactory manner. It may also be useful for obtaining a clear understanding and a qualitative solution of a practical problem because of the simplified representation which it affords.

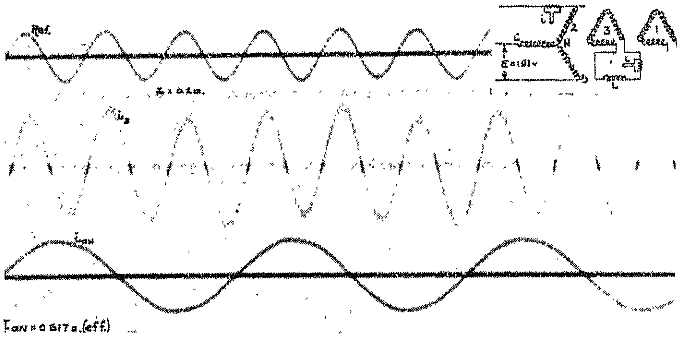

FIG. 13—DELTA CURRENT AND LINE CURRENT FOR AN INDUCTIVE LOAD IN THE DELTA CIRCUIT

($X_l$ = 290 ohms; $L$ = 0.77 henrys)

Since the triple-frequency circuit is a distinct and separate one, it should be a relatively easy matter to solve most network problems, although in some cases the networks may be too extensive to permit of a simple solution. In all calculations, it should be kept in mind that the triple-frequency no-load and leakage impedances are not constant quantities, and hence must be measured at the particular value of saturation applying to the problem under consideration. This is also the case for the triple-frequency generated voltage. The variation of these quantities as a function of fundamental applied voltage is very clearly brought out by the curves of Fig. 3. The assumption that the generated voltages in transformers of different banks of a system are in phase may lead to errors. Line drop resulting from fundamental frequency load currents may cause the triple-frequency generated voltage to be considerably out of phase. The value of the no-load impedance also may change due to core saturation effects at triple-frequency resulting from magnitude and phase angle of the third-harmonic current. Errors due to this latter cause are not large except for large triple-frequency currents when resonance is approached.

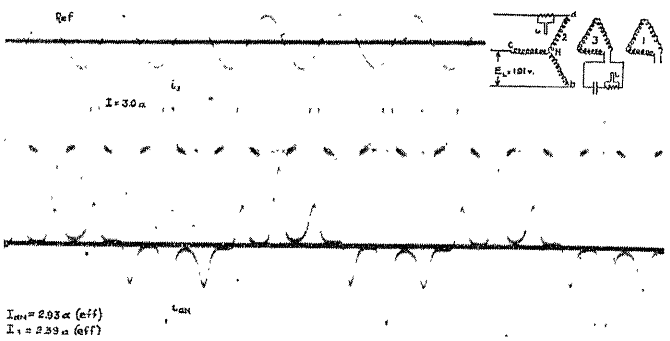

FIG. 14—DELTA CURRENT AND LINE CURRENT FOR A CAPACITIVE LOAD IN THE DELTA

($C$ = 2.0 $\mu$f.)

The previous discussion of various types of load in the delta circuit has a direct application to an actual power system. The loads introduced in the delta have an effect similar to a load from line-to-neutral on a star-connected grounded-neutral transmission system.

The resistance in the delta may represent the resistance of a three-phase load, or of the line and grounded neutral return circuit of the star-star connected transmission system. Generally, line resistances are comparatively small and may not be of large practical importance in the triple-harmonic circuit.

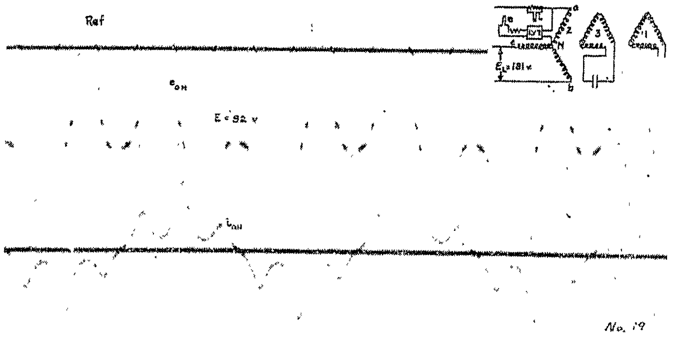

FIG. 15—LINE-TO-NEUTRAL VOLTAGE AND LINE CURRENT FOR A CAPACITIVE LOAD IN THE DELTA

($X_c$ = 1,572 ohms; $C$ = 1.69 $\mu$f.)

The external inductance inserted in the delta may be compared to the inductance of a load or of the line conductor. Here again line reactances are usually small compared with the no-load reactance of transformers and their effect on the third-harmonic voltages and currents may be slight.

For the case of the capacitance, the practical application is of considerable importance. The capacitance inserted in the delta gives the same effect as does the capacitance-to-neutral of the line conductors. A relatively small value of capacitance is necessary to produce a resonance condition, since the no-load reactance of the transformer is high. This is the actual condition which may exist on a transmission line, due to the fact that the capacitance from line-to-neutral (ground) is relatively small. Thus a resonance condition of third-harmonic current may actually occur on a transmission system if the line capacitance happens to be of the proper value. If resonance does exist on a system, a large third-harmonic current will flow, and dangerously high voltages may appear across the transformers. Also a large third-harmonic current tends to cause bad inductive interference in neighboring communication lines.

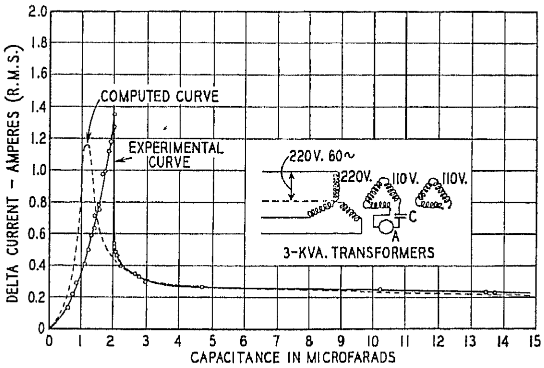

Fig. 16—Third-Harmonic Resonance with Capacitance Inserted in Delta

## Conclusions

From the results of this investigation, the following conclusions have been drawn.

1. The equivalent circuit as adopted with the inclusion of a triple-harmonic generator is a true representation of actual conditions existing in a transformer.

2. The triple-frequency equivalent circuit may be used to solve triple-harmonic network problems, provided the necessary data are available. Practically the only limitation to its use is the complexity of the network.

3. The equivalent circuit solution will be very accurate for conditions in which the third-harmonic excitation is normal or nearly so. For cases in which the system voltages are abnormal, either in wave form or in magnitude, the no-load impedance and "generated" voltages of the transformers must be determined for these particular conditions of saturation before a high degree of accuracy can be expected from the equivalent circuit solution.

4. Third-harmonic resonance will occur on a system when the external equivalent capacitive reactance of the circuit is equal to the no-load inductive reactance of the transformer at triple-frequency.

5. Third-harmonic resonance results in abnormally large triple-frequency currents which produce transformer core saturation at this frequency thus changing the no-load impedance of the equivalent circuit.

6. Resonance at triple-frequency produces a large distortion of the system line-to-neutral voltages which may have dangerously high maximum values resulting in insulation breakdown.

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## Discussion

**P. W. Blye:** Although, in general, triple harmonic components from transformers are smaller than those arising in rotating machinery operated with grounded neutral,[1] in some cases the former have had an important bearing on the inductive coordination of power and telephone systems. The paper of Professor Morgan and Messrs. Bairos and Kimball is therefore of interest from that standpoint. The problem of harmonics from transformers has been recognized by Project Committee 1C on Wave Shape of the Joint Subcommittee on Development and Research —N.E.L.A. and Bell System, and that committee is at present engaged in a rather extensive investigation of the wave-shape characteristics of transformers.

My experience with several sets of tests on transformers similar to the tests made by the authors bears out their general conclusion that, at a given excitation or over a narrow range of excitations, the equivalent T-network described in their paper presents a simple and accurate method of dealing with triple harmonics arising in two-winding transformers. One or two points brought out in the paper incidental to the general conclusions, however, are not in agreement with my experience.

The paper states that the total leakage impedance as measured by the usual short-circuit method (multiplied by the order of the harmonic if measured at fundamental frequency) was found to be considerably in error as compared to the sum of the individual leakage impedances used in the equivalent circuit and observed at normal excitation by the delta-opened-delta method. My experience is that this is not necessarily the case. Consider, for example, a small 60-cycle, three-phase shell-type model transformer on which a number of such tests have been made. In the case of two windings located near the center of the core window of the model transformer, the difference between the total leakage impedance determined from a short-circuit test and the sum of the individual impedances at normal saturation amounted to not more than 1 to 2 per cent. The total leakage impedance observed with 140 per cent normal voltage applied was found to be of the order of only 4 or 5 per cent less than in the short-circuit test. Even in the extreme case of two windings located at opposite ends of the core window immediately adjacent to the yoke, the difference between the total leakage impedance under short-circuit conditions and the sum of the individual impedances at normal saturation was found to be only about 2.5 per cent. At 140 per cent normal voltage the total leakage impedance of these two windings decreased to about 15 per cent less than in the short-circuit test.

The paper also makes a statement to the effect that the individual leakage impedances decrease with increasing excitation. While this appears to be more or less generally true of the total leakage impedance, in certain cases the leakage impedance associated with one winding of a two-winding transformer has actually been found to increase slightly with increasing excitation.

Fig. 6 of the paper implies that the triple harmonic equivalent circuit of a three-winding transformer may be developed very simply from that of a two-winding transformer by merely adding a third branch made up of the individual leakage impedance of the third winding.

Boyajian has demonstrated[2] that, with respect to load currents, a three-winding transformer may be resolved into a convenient three-terminal network. Such a network could, no doubt, be developed for use in considering triple harmonics arising from an external source as, for instance, from a grounded neutral generator, which completely override those arising in the transformer. This network, however, as pointed out by Boyajian, does not apply to magnetizing currents. Test data which I have seen bear out the idea that the leakage impedances in a three-winding transformer are not quantities which can be associated definitely with the individual windings, even at a given excitation, irrespective of the condition of the other windings. As far as I know, a satisfactory and reasonably simple equivalent circuit for harmonics arising in a three-winding transformer which would be generally applicable, irrespective of the method of connection of the various windings, has not yet been devised.

Fig. 16 of the paper illustrates very well the dependence of the shunt element of the equivalent circuit, called by the authors the "no-load impedance," upon the third harmonic excitation. The difference between the calculated and measured resonance point is no doubt due to the change in the "no-load impedance" for the condition of resonance due to the abnormally large third harmonic current circulating in the secondary.

**A. Boyajian:** Referring to Fig. 6 of the paper, a single equivalent circuit for Bank No. 3 is not applicable to both the currents produced by $E_3$ and for those produced by $E_2$. The division of leakage reactance between $S_3$ and $T_3$, will be to a first approximation rather independent of $P_3$ but dependent on the core; whereas, the division of leakage reactance between $S_3$ and $T_3$, so far as $E_2$ is concerned, will be independent of the core but dependent on $P_3$ in accordance with three circuit equations. A single equivalent circuit to satisfy both conditions would have to be a six-link affair, and, therefore, very difficult to construct and use. Accordingly, if the equivalent circuit is to be a simple three-link network, the two sets of triple frequency currents have to be solved separately, by different equivalent circuits, and then combined. Reasonably good results claimed by the authors, with the use of a single three-link equivalent circuit, would seem to imply that, in the case under consideration, the two equivalent circuits did not happen to differ from each other materially.

**H. V. Carpenter:** I did not notice in the paper a definite statement as to the magnetic conditions existing during the tests. If three single-phase transformers were used each phase had its own independent magnetic core. If one type of three-phase transformer was used the three flux paths would be partially but not wholly independent while if the other type was used any flux passing through one core returned through the other two.

In this latter case the third harmonic flux would find no return path. It seems likely that the three different conditions would give somewhat different results.

**D. I. Cone:** Despite the number of publications dealing with the behavior of triple harmonics arising in three-phase circuits due to transformer magnetization, there still appears to be a need for the presentation of methods for quantitative prediction of the behavior of given networks. This paper is a helpful contribution toward that end.

Considering Fig. 3 and the related discussion, it is noted that a "no-load" impedance of about 1,050 ohms is obtained at normal voltage. An approximation to this value is obtained from the single-phase test data of Fig. 1, which indicates a third harmonic current of 0.119 amperes at 220 volts, combined with an assumption for the "open circuit" third harmonic voltage. If this be taken as 50 per cent of the 60-cycle voltage, a value of 925 ohms is obtained. This value, of course, includes the third harmonic impedance of the 60-cycle source, but evidently provides a much closer approach to the third harmonic impedance value than an attempt to obtain it from the 60-cycle reactance of the transformer.

Referring to Fig. 16, it is most encouraging to observe that even at the resonance point it was practicable to predict the approximate magnitude of the third harmonic current.

Desirable extensions of this study would concern the distribution of triple harmonics in three-winding transformers and associated lines.

**L. J. Corbett:** In the triple-harmonic circuit the current and voltage relations are rather complex. The triple-harmonic voltage is superposed upon the fundamental frequency voltage at a particular phase relation, and triple-harmonic currents flow in a circuit which is also carrying fundamental-frequency current. The so-called triple-harmonic impedance of a transformer will vary, therefore, because of the changing state of saturation of the core, a rough average existing for each value of fundamental-frequency voltage. If the phase relations of the triple-frequency to the fundamental-frequency quantities change, the triple-frequency impedance changes also. Further, the demagnetizing effect of the triple-frequency current in the transformer is the important feature in measures for suppressing the flow of triple-harmonic currents in power systems having grounded neutrals. The open-delta voltage divided by the closed-delta current seems rather inexact as a measure of the triple-harmonic impedance existing under actual operation.

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[1] See *Telephone Interference from A-C. Generators Feeding Directly on Line with Grounded Neutral*, by J. J. Smith, A.I.E.E. Trans., Vol. 49, No. 2, April 1930.

[2] *Theory of Three-Circuit Transformers*, A. Boyajian, Trans. A.I.E.E., Vol. XLIII, 1924.

The equivalent circuit method is convenient, and is fairly accurate when the elements are single transformer banks separated by impedance, as in the tests described in the paper. However, because of the demagnetizing effect, one transformer bank connected $Y/Y$ with grounded neutral will force but little more triple-harmonic current through two $Y$/delta banks (with grounded neutral) of a given size than it will through one. Two equal $Y/Y$ banks will force practically twice as much triple-harmonic current through one $Y$/delta bank as will one of them alone, though the triple-harmonic voltage and outside impedance remain the same. For conditions which exist on most power systems *i.e.*, multiple banks at power houses and substations and divided triple-harmonic circuits, the equivalent circuit method of calculation has serious limitations.

The data and oscillograms presented in the paper are of considerable interest. An important feature which should not be overlooked is that the voltage which causes the flow of triple harmonic currents is due to a lack in the exciting current of simple triple-harmonic currents, which are in a definite phase relation to the fundamental wave of applied voltage. (See Fig. 1 of the paper.) Any change in phase relation of the secondary triples will tend to be compensated for by a primary triple of such magnitude and phase that the resultant triple-harmonic ampere turns will be such as would be required in the primary exciting current to reproduce the applied fundamental-frequency voltage wave.

**E. G. Cullwick:** In this paper the authors state that the harmonics in the exciting current of a transformer are produced by voltages of like frequency produced in the transformer itself, "due to the action of the steel core." I do not think that this is a very good description of what actually happens. If the applied voltage is truly sinusoidal, then the induced emf in the transformer will be almost exactly sinusoidal, and will require a sinusoidal flux variation for its generation. Due to the varying reluctance of the iron core, the magnetizing current necessary to produce this flux will not be sinusoidal but will contain a strong third and higher odd harmonics. To represent these harmonics in an equivalent circuit it is logical to replace the varying impedance of the transformer by a constant impedance and a generator of odd harmonics, but I do not think that it is accurate to state that the harmonics are actually due to emf's generated in the transformer windings.

The third harmonic emf's appearing in the secondary phase voltages of transformers with their primaries connected in star without a neutral lead are caused by a third harmonic in the flux which is due to the suppression of the third harmonic in the exciting current. This third harmonic is necessary if a sinusoidal flux variation is to be obtained, and its absence will cause the flux-wave to contain a third harmonic. With a core-type three-phase transformer these harmonic fluxes cannot exist. Have the authors considered this case in connection with the equivalent circuit diagram?

Were any measurements made for the ninth and higher harmonics, and also were the third harmonic measurements entirely free from the effects of these higher harmonics?

**C. W. Frick:** The paper gives the results of an experimental study of the triple harmonics in three-phase transformer banks. It will be noted that measurements were made with a harmonic analyzer. This method permits a wider range of measurements and gives better accuracy than methods previously used for measuring the triple harmonics. The authors compare the experimental results with the results calculated for the equivalent circuit for the triple harmonics in a two-winding transformer proposed by H. S. Osborne in 1915 and used by several investigators. It seems to the writer that the limitations of the equivalent circuit brought out by the experimental data in the paper should be considered further.

In examining the equivalent circuit it is well to keep in mind the actual behavior of the triple harmonics. A single path for the triple-harmonic exciting current in a three-phase bank of two-winding transformers can be provided by connecting one of the windings delta and connecting the other winding so that it is open-circuited for the triple harmonics. If the impedance of the delta winding is zero the triple-harmonic voltage is zero. If the impedance of the delta winding is appreciable a triple-harmonic voltage sufficient to overcome the impedance voltage due to the triple-harmonic exciting current is set up. If the impedance is increased, for instance by adding impedance in one corner of the delta winding, a larger triple-harmonic voltage is required. Furthermore, the triple-harmonic exciting current with appreciable impedance in the delta winding is different from the triple-harmonic exciting current with zero impedance because it requires a different exciting current to set up the necessary triple-harmonic voltage. In the equivalent circuit the behavior of the triple harmonics is represented by a constant triple-harmonic voltage ($E$) acting through a high impedance designated $Z_{NL}$ in Fig. 5 of the paper. If there is only one path for the triple-harmonic current the equivalent circuit has only one of its branches closed and it amounts to a simple series circuit; impedance in the actual path (delta winding) is represented by impedance added in series.

In the paper an equivalent circuit is set up using values of the voltage $E$ and the impedance $Z_{NL}$ determined experimentally under specified conditions. The results show that the equivalent circuit set up in this manner behaves very nearly like the actual circuit when the added impedances are such that the triple-harmonic exciting current does not differ greatly from the normal value, as might be expected. The data also show, however, that the equivalent circuit may not behave like the actual circuit with impedances which require a triple-harmonic exciting current differing materially from the normal value. This shows that the equivalent circuit is subject to limitations which should be kept in mind.

The impedance $Z_{NL}$ has been shown from theoretical consideration to correspond to the open-circuit self-inductive reactance of one winding in a 1-to-1 ratio transformer where the leakage is small; this shows the order of magnitude.[3] A distinction must be made between the effective magnetizing reactance for the third harmonic and the effective magnetizing reactance for the fundamental because the core passes through a wide range of inductance values. It is shown in the paper that the value of $Z_{NL}$ for the third harmonic cannot be taken as three times the open-circuit reactance for the fundamental but must be determined in some other manner. The equivalent (internal) impedance obtained for the third harmonic varies with the magnitude and phase of the third-harmonic circuit which flows. The authors use an impedance value obtained under specified test conditions. Three transformers are connected $Y$ on the primary side and delta on the secondary side, as in Fig. 2 of the paper, and the ratio of the triple-harmonic voltage per transformer with the delta opened to the triple-harmonic current in the closed delta is called the "no-load" impedance for the triple harmonics at the particular excitation voltage used. In many instances where the transformers are available for making this test it may be almost as easy to set up a circuit similar to the actual circuit being studied and measure the exciting current directly. The equivalent circuit would then be superfluous.

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[3] The constants of the equivalent circuit are discussed in a paper by A. Boyajian entitled *Resolution of Transformer Reactance into Primary and Secondary Reactances*, A.I.E.E. TRANS., 1925, p. 805.

The increase of the third-harmonic exciting current with added capacitance within a certain range in the delta winding which has been observed by other investigators is discussed in the paper. It appears from the equivalent circuit as if resonance might occur between the added capacitance and the impedance $Z_{NL}$ at the frequency of a triple harmonic. The impedance $Z_{NL}$ does not appear in the actual circuit. The equivalent impedance which it represents varies with the magnitude and phase of the triple-harmonic current as pointed out above and true resonance cannot exist. It would seem preferable to consider the behavior observed merely as a condition of distortion without reference to resonance.

The leakage impedances associated with the windings may be of more value for some purposes than the "no-load" impedance. Fig. 4 of the paper gives values of leakage impedance associated with one of the windings and shows the variation with excitation voltage. It would be of interest to compare this with the leakage impedance associated with the other winding which is not given in the paper and to compare the sum of the two with the total leakage impedance for the two windings. In tests made by the writer the leakage impedances associated with the two windings varied with the excitation voltage but their sum remained about the same over a wide range of excitation voltages. The arrangement of the core and windings of the transformers tested would also be of interest.

**T. H. Morgan:** There is a considerable divergence in the manner in which triple-harmonic phenomena in transformers are viewed by various people. However, many of the conceptions of the phenomena involved, which at first thought appear to be at variance, are found to be reasonably in accord when fully analyzed.

The authors agree with Mr. Blye that it is not necessarily true that the total leakage impedance of a transformer as measured by the usual short-circuit method will always be higher than the correct value. It happened to be so in the case investigated by the authors, but it would seem that the amount of this discrepancy would depend on the proportion of the leakage flux passing through the transformer core and the degree of saturation of the core by the main flux.

The explanation of the inaccuracy involved by the use of the single three-link network equivalent circuit in Fig. 6 to calculate currents from all sources in a three-circuit transformer, as pointed out by Mr. Blye and Mr. Boyajian, is quite justified. However, it should be clearly understood that this circuit is not the one used in the test described in this paper. It was given only as an illustration of the application of the equivalent-circuit method to a practical case. The actual circuit investigated contained no three-circuit transformer and is given in Fig. 7 of the paper. Consequently the small discrepancies shown by the authors between their test and computed values cannot be charged to this account.

In reply to the question of Professor Carpenter regarding magnetic conditions of the test it should be made clear that individual single-phase transformers were used in each bank on the test.

Mr. Corbett believes that the triple-harmonic impedance as obtained by the authors will prove to be inexact when the phase angle of the triple current changes. This is contrary to the results of the investigation, as the authors show that measurements over the complete range of 180 deg for the triple-harmonic current give values having close agreement with the computed currents on the basis of constant impedance. The application of the equivalent-circuit principle to the case of multiple banks on a power system appears to offer no particular difficulty and should give reasonably correct results when correctly applied.

The question of the manner in which we view the cause of the harmonic currents has been interestingly discussed by Professor Cullwick. The viewpoint expressed by the authors is arrived at from the following reasoning. The harmonic currents are purely superimposed phenomena. It is impossible to obtain a current of any frequency in a circuit without an emf as its cause. With a true sinusoidal voltage applied to a transformer we have harmonics of current in the exciting current. Since the harmonics of voltage which cause them are not present in the generator they must exist in the transformer. As an example, consider the simple case of a single two-circuit transformer with the secondary winding open-circuited and true sinusoidal voltage applied to its primary circuit. If the leakage impedance of the primary winding and also the impedance of the generator be considered zero, there would be no harmonic voltages in the transformer. However, if this circuit has any impedance whatever as in the practical case the transformer supplies the harmonic voltage required to force each component of harmonic current through the circuit. In other words, the harmonics of current are a result of harmonics of emf in the transformer.

Measurements were made by the use of a harmonic analyzer which gives a high degree of accuracy for the measurement of any harmonic entirely uninfluenced by the effects of other harmonics. Certain measurements were made for the ninth and other harmonics but an analysis has only been made for third-harmonic effects, these being by far the most important because of greater magnitude.

The remarks of Mr. Frick suggest a number of points for discussion. The assumptions involved by equivalent circuit representation can possibly be explained by comparing the action of the triple-frequency transformer flux with that of the flux in a polyphase non-salient pole alternator. If we consider such an alternator armature circuit having extremely low leakage reactance and resistance we have a circuit which is closely analogous to the triple-frequency circuit in the transformer. The alternator armature open-circuit condition can be compared to that of the transformer having the path for the triple-frequency current blocked in all windings. If the alternator armature be short-circuited the flux will be reduced to a very low value by armature reaction which corresponds to the case of a closed-delta on the transformer bank where the triple-frequency path is short-circuited. These may be considered the two limiting conditions. Various other effects of armature reaction can be obtained in the alternator by inserting different amounts and types of impedances in the armature circuit. This corresponds to inserting external impedance in the delta or in any other circuit of the transformer permitting the flow of triple-frequency current. In this latter case the amount of the current and flux will change with the amount of the impedance while the phase angle will be governed by the kind of impedance used in either the alternator or the transformer circuit. Under these conditions if the armature reaction effect in the case of the alternator be treated as a constant reactance for various amounts and angles of armature current it will be equivalent to the treatment of the "no-load impedance" ($Z_{NL}$) of the transformer as a constant for all conditions of triple-frequency current. Theoretically such an impedance will not be a perfectly constant quantity for either the alternator or the transformer as it will vary somewhat with current magnitude and phase angle. As a matter of fact the investigation of the authors shows clearly that the impedance ($Z_{NL}$) remains practically constant over a wide range of magnitude and phase angle of the triple-frequency current. Also the investigation very clearly brings out that we do get a condition of resonance (see Fig. 16) which is in rather close agreement with the calculated phenomenon on the basis of constant $Z_{NL}$. The point of resonance occurs when the external capacitive reactance equals $Z_{NL}$. At this point we would expect the greatest error in the method because of the extremely high triple-frequency currents. The last point in Table I corresponds to such conditions and the error is easily explained by referring to the curves in Fig. 16 near the point of resonance.

# Radio Plant of R.C.A. Communications, Inc.

BY H. H. BEVERAGE,* C. W. HANSELL,* and H. O. PETERSON*
Associate, A.I.E.E. Associate, A.I.E.E. Associate, A.I.E.E.

*Summary:—This paper describes the radio plant of R.C.A. Communications, Inc. Charts are given showing the growth of the services handled through this plant. Some of the technical requirements of the service are discussed and the means for meeting these requirements disclosed. In describing the facilities in use, they are divided into three general divisions, namely, central offices, transmitting stations, and receiving stations. Most of the recent development of this plant lies in the field of short wave operations, i. e., frequencies between 3,000 and 30,000 kc.*

* * * * *

## HISTORICAL OUTLINE OF THE R.C.A. COMMUNICATIONS SYSTEM

THE Radio Corporation of America, through its subsidiary R.C.A. Communications, Inc., operates a world wide radio communications network between the United States and about forty foreign countries. The major terminals of the system are in New York and San Francisco. There are supplementary centers in Honolulu, Manila, and Havana.

The Radio Corporation of America opened its transoceanic services in 1920 using low radio frequency radiation, between 15 and 30 kilocycles, produced by means of Alexanderson alternators.[1,2,3] Following the discovery that a large band of high frequencies could be used for long distance communication these high frequencies have also been used since 1924. At the present time they carry nearly all the long distance radio traffic. Vacuum tube transmitters are used exclusively in producing the high-frequency radiation.[4,5,6]

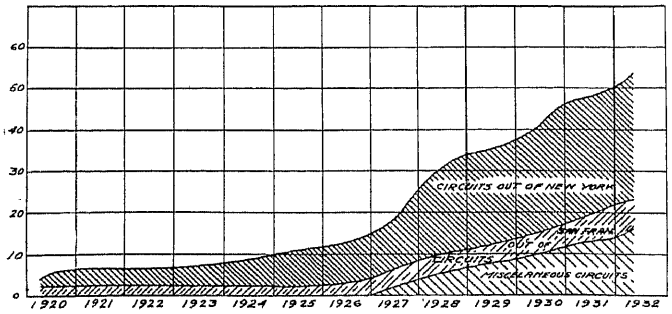

FIG. 1—GROWTH OF R.C.A. INTERNATIONAL TELEGRAPH CIRCUITS

On the Atlantic coast, at the present time, a total of about 8 low-frequency and 35 high-frequency transmitters, controlled from New York, are located at Rocky Point, Long Island, N. Y., Marion, Mass., New Brunswick, N. J. and Tuckerton, N. J.

All incoming traffic for New York is handled through a central receiving station at Riverhead, Long Island, N. Y. This station has about 16 low-frequency and 40 high-frequency receivers.[1,3,5,7,8]

On the Pacific coast 12 high-frequency transmitters, controlled from San Francisco, are located at Bolinas, California. About 20 high-frequency receivers are located at Point Reyes. There are also several low-frequency receivers located at Marshall and remotely controlled from the Point Reyes station.

Fig. 1 shows the growth in the number of circuits operated, starting with 6 in 1920 and expanding to 54 in 1932. The rapid increase in the number of circuits, after 1927, was made possible by the introduction of high-frequency equipment, the first cost of which is relatively low.

Fig. 2 is a map of the world showing the more important circuits of the R.C.A. system. This system, in conjunction with branch radio circuits and wire line networks in the countries served, reaches practically the whole civilized world.

Fig. 3 shows the growth of the R.C.A. international telegraph traffic. It is of interest to note the rapid increase in high-frequency traffic during 1927, 1928, and 1929. For the past several years practically all the traffic with South America and Pacific points has been handled on high frequencies. Low frequencies are still used across the North Atlantic, to supplement the high frequencies, because of occasional disturbance to high frequencies from severe magnetic storms over this route.

The total traffic curve shows some interesting yearly cycles. The load is minimum during the summer and reaches a sharp maximum in December, largely due to the exchange of Christmas and New Year greetings.

## CENTRAL OFFICE EQUIPMENT

All traffic operations are centralized in traffic offices conveniently located in New York City, San Francisco, and other terminals. The offices are connected by wire lines with the transmitting and receiving stations, which are usually some distance away.

Messages to be sent are transferred to paper tapes by means of perforators with a keyboard similar to ordinary typewriters. The perforated tape is then fed through automatic transmitters which impress the dots and dashes of the Continental Morse code upon the control lines to the transmitting stations.

The speed of transmission is held substantially constant over considerable intervals, the speed depending upon circuit conditions and traffic load. On busy circuits a speed of 100 to 125 words per minute is

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*Engineers, R.C.A. Communications, Inc., 66 Broad St., New York.

1. For references see Bibliography.

*Presented at the Pacific Coast Convention of the A.I.E.E., Vancouver, B. C., August 30-September 2, 1932.*

usually maintained, but speeds above 200 words per minute are occasionally used. On less busy circuits it is customary to operate at speeds of 50 to 60 words per minute so that a single operator may be capable of handling each end of the circuit.

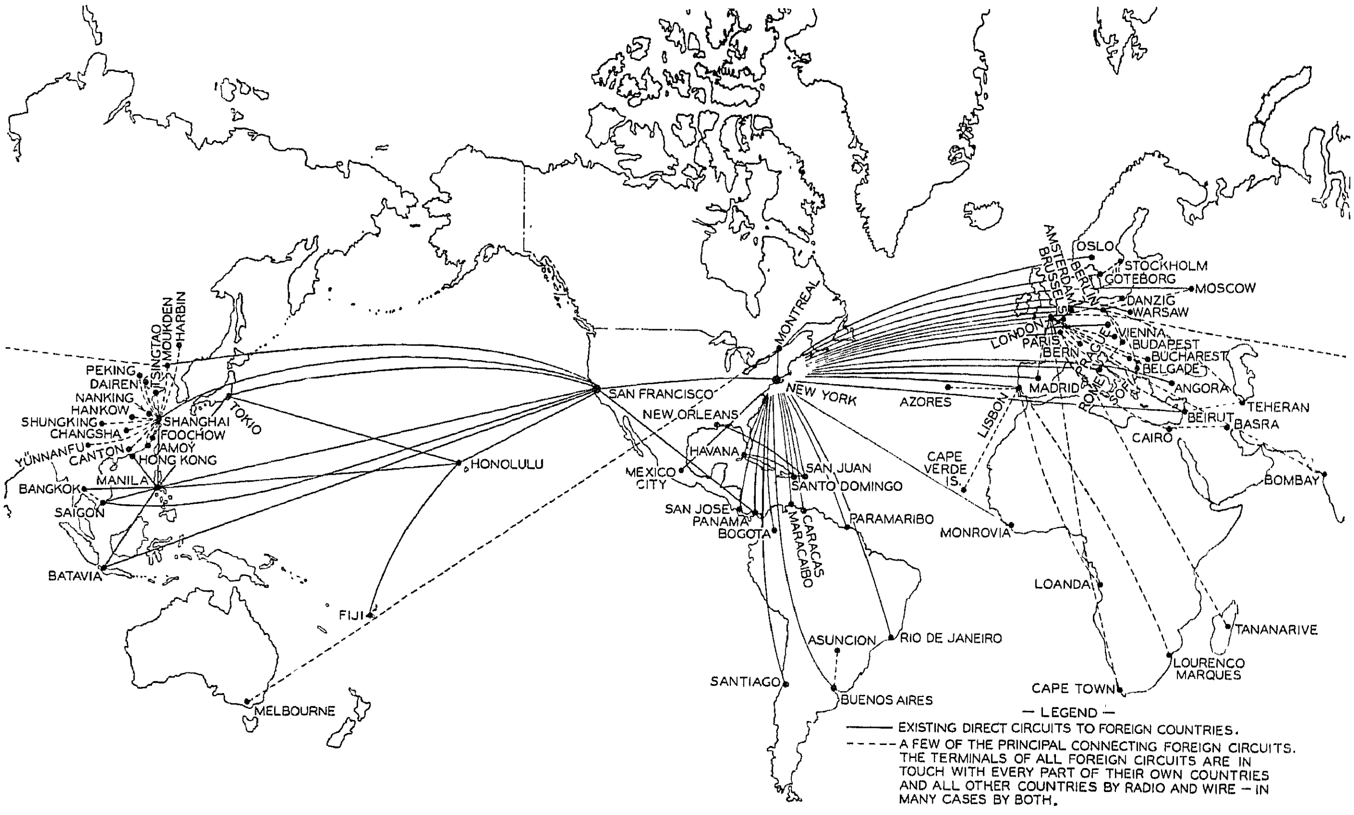

Fig. 2—World Map Showing R.C.A. Circuits

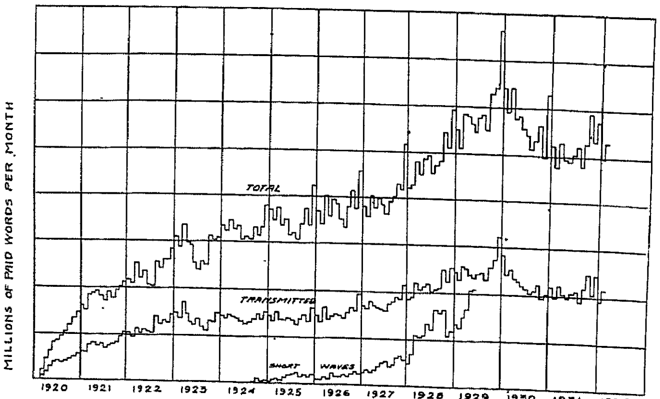

Fig. 3—Growth of R.C.A. International Telegraph Traffic

The signals from the receiving station arrive in the central offices in the form of keyed tones. These are amplified, rectified, and then plugged through to any desired receiving table to operate an automatic recorder. The recorder has a light movable coil suspended in a strong magnetic field. Signal currents through this coil cause it to move a light lever carrying a small silver tube through which ink is impressed upon a moving paper tape. The signals appear as undulations in ink line upon the tape. Fig. 4 is an illustration of one form of recorder.

Tape bearing the signals is drawn at a convenient speed across a guide on the operator's typewriter from which the operator reads the messages and types them on message blanks. If the circuit operates faster than 50 or 60 words per minute, two or more operators may divide the tape between them. In this way the messages on all circuits are kept transcribed and there is no delay.

The typed messages are carried to a central point, on a belt conveyer, where they are timed, numbered, and routed according to destination, enveloped and dropped through a chute to the messenger room for immediate delivery.

Fig. 5 is a general view of a portion of the New York Central Office at 66 Broad Street. Two double rows of tables are shown with a belt conveyer in the center of each row. Receiving tables are arranged on one side and transmitting tables on the other. Transmitting and receiving operators handling messages with any one country are placed together to facilitate the handling of the circuits.

## Transmitting Stations

The transmitting stations, fundamentally, are for the purpose of performing the following operations:

a. Conversion of 60-cycle a-c. power into power of radio frequencies.

b. Radiation of the radio frequency power.

c. Accurate control of radiation frequency.

d. Modulation or keying of the radiation for the transmission of intelligible signals.

For low-frequency transmission, an Alexanderson alternator, driven by a 2,200-volt, two-phase wound-rotor induction motor, is used to produce energy at 15,000 to 30,000 cycles. Its appearance is illustrated in Fig. 7. The alternator is of the inductor type with a toothed rotor running between parallel armatures bearing 64 armature coils. The outputs of the 64 coils are combined into a single circuit by means of a transformer which delivers 100 to 120 amperes at 2,000 volts to one of several downleads and tuning coils of an Alexanderson multiple tuned antenna.

Fig. 6 is an illustration showing two multiple tuned antennas at Rocky Point. Each antenna consists of wires supported on towers 410 feet high, with 150-foot cross arms at the top. Each antenna is 1.5 miles long. The circulating energy in each, when a signal is being sent is about 700 amperes at 135,000 volts or nearly 100,000 kva. Although each antenna constitutes one of the lowest power factor circuits known, (for its frequency), its radiation efficiency is only about 10 per cent and it has practically no directivity.

A rather intricate system is used to control the frequency and to key the output of the alternator. In spite of its intricacy, this system has in service proved remarkably free from equipment failures. This freedom from operating difficulties is a direct tribute to the engineering skill of Mr. Alexanderson and the General Electric engineers who assisted him.

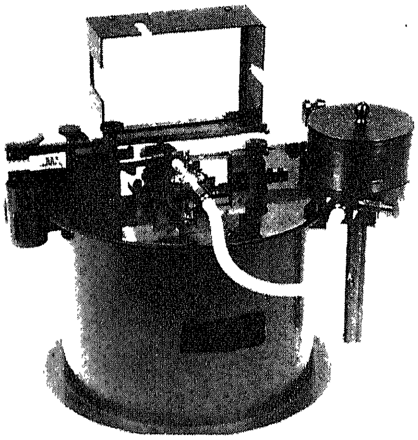

FIG. 4—A MODERN TYPE OF INK RECORDER USED ON RADIO TELEGRAPH CIRCUITS

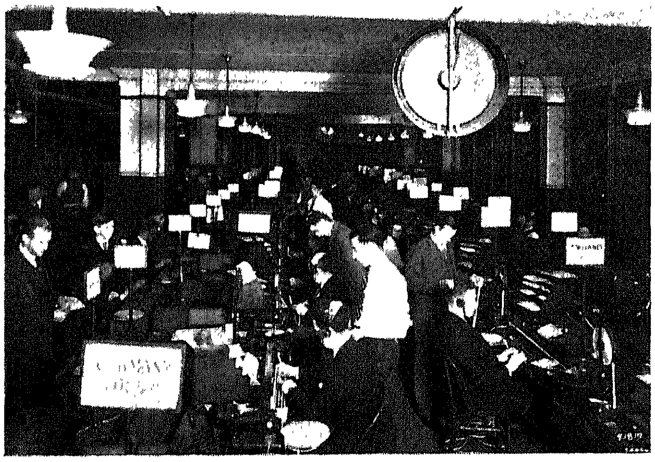

FIG. 5—A PORTION OF THE OPERATING ROOM AT BROAD STREET, NEW YORK CITY

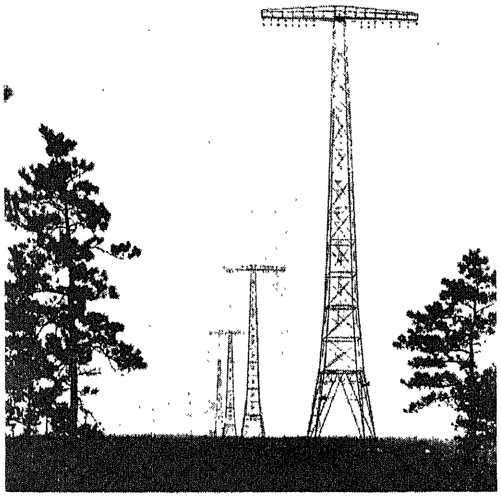

FIG. 6—THE LONG-WAVE ANTENNAS AT ROCKY POINT, N. Y.

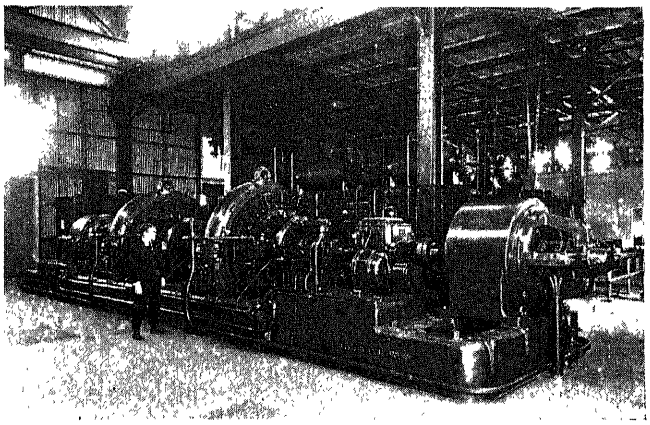

FIG. 7—ALEXANDERSON 220-KW. HIGH-FREQUENCY ALTERNATORS AT THE ROCKY POINT STATION

In high-frequency transmitters, vacuum tubes are used to convert 60-cycle power into direct current and then into power of about 5,000,000 to 22,000,000 cycles. The tubes which produce the radio frequencies are equivalent to resistances, the value of which may be varied with extreme rapidity by varying the potential upon control electrodes within the tubes.

Nearly all of our high-frequency transmitters employ relatively low-power piezo electric crystal-controlled oscillators to produce initial oscillatory currents at frequencies between about 750,000 and 3,000,000 cycles.[9] The oscillator output is then passed through a chain of vacuum tube amplifiers and frequency multipliers to obtain the final power and frequency required for transmission. The crystal oscillator provides a very constant frequency and permits the operation of transmitters with relatively small frequency separation. The Federal Radio Commission limits the frequency variations to less than 0.05 per cent on old equipment and 0.02 per cent on new equipment.

The use of frequency multiplication in the successive stages of amplifier greatly reduces the tendency for high power circuits to feed energy back to lower power circuits in a way to set up uncontrolled self oscillations in the amplifier system. This is an important feature and is almost a necessity where large power amplification is used. The use of screen grid shielded vacuum tubes and neutralizing circuits for counteracting couplings between tube input and output circuits are also very helpful in preventing spurious oscillations. The final power outputs to the antennas range between about 1 and 40 kilowatts depending upon the circuit requirements.

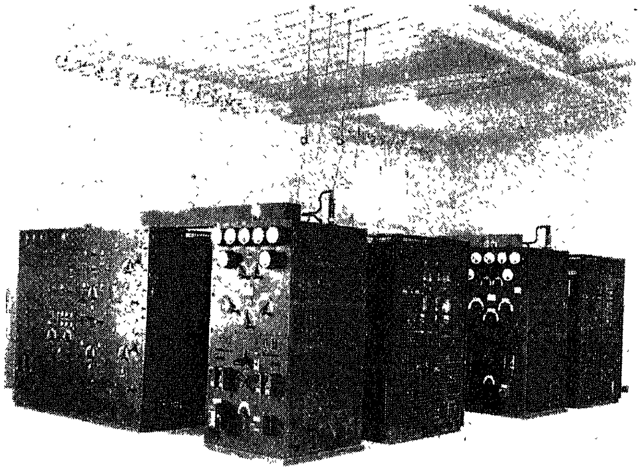

Fig. 8—A Group of 20-40-Kw. Short-Wave Transmitters at the Bolinas Station

The keying of the transmitters in accordance with telegraph signals is done by varying the electrode potentials on some of the vacuum tubes in the chain of amplifiers. This is done through electromechanical relays or through vacuum tube devices controlled from the central office. Some of the vacuum tube keying equipment is capable of functioning at speeds equivalent to more than 1,000 words per minute, and is used at these high speeds in the transmission of pictures or "photoradiograms."

The use of high-frequency radiation, with its shorter electrical wave lengths, has made it practical and economical to direct the radiation toward the distant receiving station. Consequently, directive antennas are commonly used with high-frequency transmitters.[10]

R.C.A. Communications, Inc., has successively developed and applied four different types of directive antennas known as models A, B, C, and D. Several other types have also been designed for special requirements. The models A and B radiate vertically polarized waves while models C and D radiate horizontally polarized waves. The power gain due to directivity ranges up to 80 to 1, depending upon the type and size of antenna. Due to their relatively low cost and great directivity, antennas give a high ratio of circuit improvement per dollar of cost.

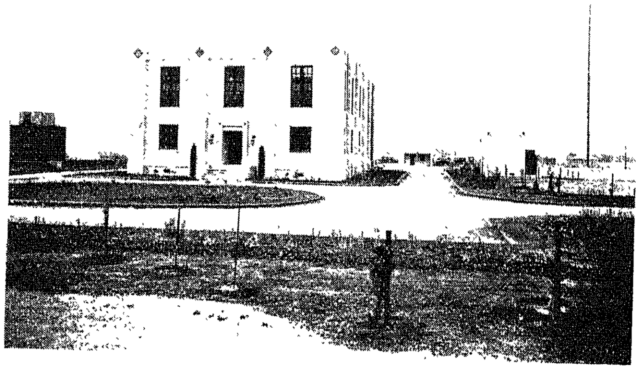

Fig. 9—The Short-Wave Transmitting Station at Bolinas, California

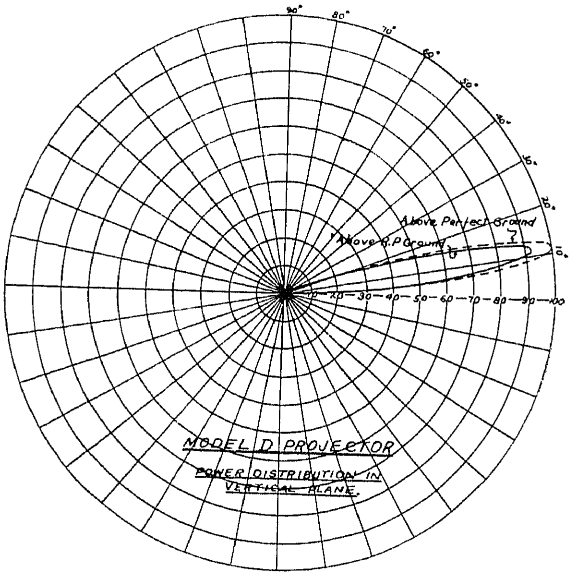

Fig. 10—Power Distribution in Vertical Plane for Model D Antenna

Figs. 10 and 11 show the directive characteristics of a two-bay model D antenna giving a power gain, over a half wave dipole at the same height as the antenna, of about 80 to 1. When used with a 40-kw. transmitter this antenna launches radiation toward the distant receiver equivalent to that which would be obtained with 3,200 kilowatts in a non-directive antenna. This is about 800 times the radiation launched toward the distant receiver from an Alexanderson alternator and low-frequency multiple tuned antenna.

Fading of high-frequency signals is a phenomenon of nature which must be overcome in a commercial radio communications system. Often the received signals vary over a great range in intensities. At times the variations are so rapid as to constitute an audio modulation, though rather slow periods of a few seconds are more common. Since it has been observed that the fading of even slightly different frequencies is not simultaneous, the effects of fading can be reduced by transmitting the same signals on more than one frequency. In some commercial transmitters the carrier wave is amplitude or frequency modulated at an audio rate, in addition to the keying, to produce side frequencies and so reduce fading by frequency diversity. However, it is preferable to reduce the effects of fading by methods applicable at the receiver such as will be mentioned later in this paper.

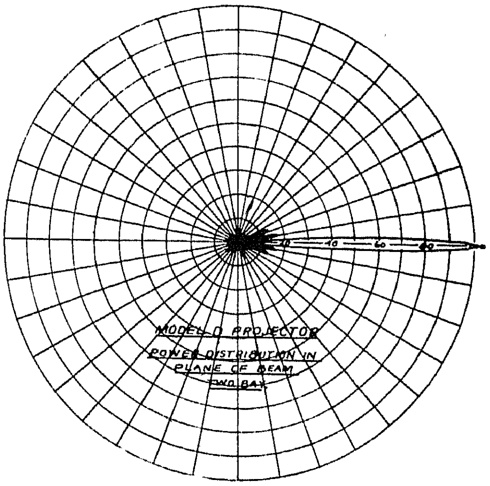

Fig. 11—Power Distribution in Plane of Beam, Two-Bay Model D Antenna

## Receiving Stations

The function of the receiving station is to select the desired signals by virtue of frequency discrimination and amplify and convert them to a form of electrical energy suitable for transmission over circuits extending to the central office. In the fulfillment of this function, several technical conditions must be effectively dealt with.

It has already been mentioned that one of the problems confronted in the operation of short wave circuits is that of signal fading. Aside from the short-period fading, which was mentioned, there are even greater ranges in intensity changes at a diurnal rate.

The diurnal variations are overcome by the use of more than one frequency channel to carry a twenty-four hour circuit. For example, the circuit from New York to Buenos Aires, operates on 20,455 kc. during daylight hours and on 8,809 kc. at night. Some of the circuits from New York to Europe require three properly chosen frequencies to insure reliable service.

The short period fading is overcome by means of automatic volume control and by a system of receiving with spaced antennas which has become known as the diversity system.[8] The spacing of these antennas is usually well over ten wavelengths. Automatic volume control is a form of automatic voltage regulation. The rectified signal is caused to react upon the overall gain of the receiver in such a manner that the gain is increased as the signal strength decreases. The relative variations of output voltage are thereby made much smaller than those of input voltage. This form of gain regulation, together with the utilization of the diversity principle, makes it possible to obtain a commercial degree of stability on a short wave circuit.

In the diversity system, advantage is taken of the fact that fading does not occur simultaneously at points geographically spaced. The extent to which fading at spaced points differs is illustrated in Fig. 12. This illustration shows a 19,180-kc. signal from Portugal as recorded simultaneously on four ink recorders at Riverhead, N. Y. The three upper strips of tape in each group were taken on single receivers connected to receiving antennas situated at spaced points. The fourth strip of tape is the result of combining the outputs of the three single receivers.

Switching arrangements are provided to allow the individual receivers of the diversity units, to be used individually, if desired. Frequently, it is convenient to leave two receivers operating on the diversity arrangement, while the third receiver is used independently to observe a second transmitter that is to be substituted.

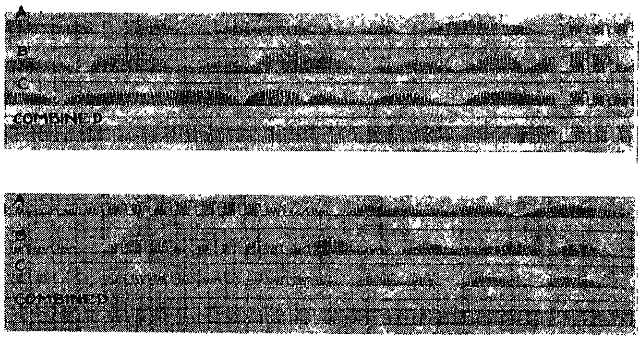

Fig. 12—Simultaneous Recorder Tapes Showing Random Fading at Three Spaced Antennas

To prevent mutual interference between the various receivers, each unit is carefully shielded and battery power to each circuit is fed through low pass filters. All receivers in a station are usually operated from a common battery system continuously charged through filter circuits.

The amount of improvement due to the use of the space diversity system is dependent upon the range of fading. Thus, if there is no fading, one antenna will do as well as three combined. If, on the other hand, the signal periodically fades to zero, no amount of gain in a single receiver can give a signal free of drop-outs, whilst the diversity system might give continuous output. In practise, the improvement due to diversity comes somewhere between these two extremes. As a general rule, a three antenna diversity system will give an improvement of approximately threefold as compared with a single antenna system.

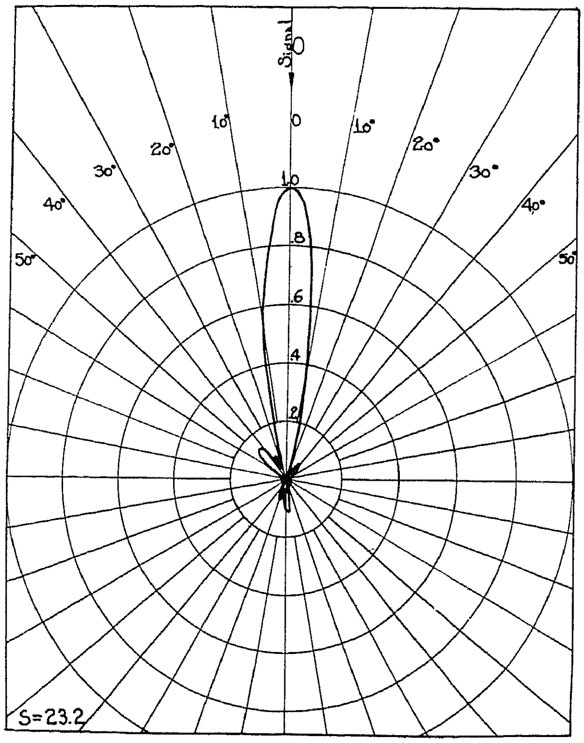

FIG. 13—OBSERVED HORIZONTAL PLANE DIRECTIVITY OF RECEIVING ANTENNA

Another quality becomes apparent in the operation of a diversity system. That is, the matter of reserve apparatus on a given channel. Some of the adjustments of a short wave receiver are so critical that in making a retune, the signal might be momentarily lost due to over-shooting of the adjustment or to error of judgment. With three receivers normally carrying the circuit, any two will carry the signal fairly satisfactorily while the receiving engineer makes an adjustment of the third. This enables more continuous operation of the circuit which is important where high traffic capacity is contemplated.

To exclude as much as possible of undesired radiations such as atmospherics and locally generated disturbances, directive antennas are used. These antennas are responsive only to those signals which come from the directions toward which they are pointed. The antennas used are aperiodic, making it possible to simultaneously receive a group of different frequencies on one antenna. Their directivity, however, makes it necessary to have a number of different antennas to take care of circuits coming from different directions. At Riverhead, thirteen sets of antennas are provided. Each set consists of three spaced antennas making a total of thirty-nine.

A typical directive diagram, showing the horizontal directivity of one of these antennas, is shown in Fig. 13. This diagram was obtained experimentally by means of a transmitter carried in an airplane flying at an altitude of 1,200 feet along a circle of five miles radius about the antenna as a center.

The area of the polar diagram is a measure of the ability of the antenna to reduce the noise level. The factor *S*, indicated as 23.2 on this diagram, is the ratio of the area of the circle whose radius is equal to the greatest radius of the polar diagram to the area of the polar diagram. This ratio is the numerical improvement in signal to noise power ratio due to directivity if the noise sources are uniformly distributed about the receiving site. Expressed in transmission units, the improvement would be, in this case, 13.9 db.

The directivity in the vertical plane as determined experimentally by an airplane at three miles distance is shown in Fig. 14. It will be noted this diagram indicates a marked discrimination against radiations originating at ground level. This property is of decided importance since locally generated disturbances such as those radiated by motor car ignition systems, electrical machinery, power lines, etc., usually emanate from points at substantially ground level.

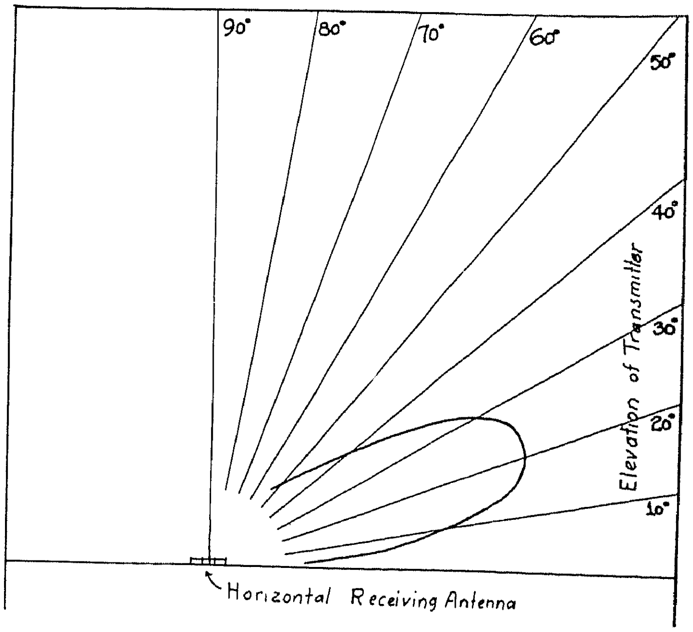

FIG. 14—OBSERVED VERTICAL PLANE DIRECTIVITY OF RECEIVING ANTENNA

In order to reduce the amount of radio frequency voltage induced directly into the transmission lines, a special design is used. In this design, four wires constitute one line, the opposite corners being connected in parallel. The electrical center of the two sides of this line are nearly coincident, and, consequently the pickup is small.

Passing into the receivers and through the tuned radio frequency amplifiers, the signals are heterodyned to audible frequencies. Most of the selectivity of the receivers is obtained in the audio frequency stages. By means of low pass filters, it has been found practical to reduce the band width to 6,000 cycles. With increasing stability of transmitter frequencies, it should eventually be possible to reduce this band width still further.

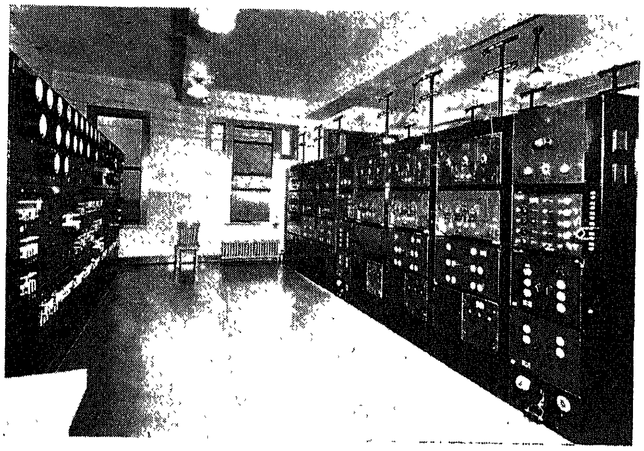

FIG. 15—FRONT VIEW OF RACK CONTAINING TWO COMPLETE DIVERSITY TELEGRAPH RECEIVERS, POINT REYES, CALIFORNIA

Fig. 16 shows the tone line control board at Riverhead. All signals, both long-wave and short-wave, pass through this board. All orders from the central office are passed to the supervisor at this control board, who in turn, issues orders to the engineers at the receivers in both the short-wave and long-wave buildings, through the medium of a public address system.

By operating a telephone key, the supervisor can listen to any signal and at the same time, the volume of signal going into the line is indicated on a volume indicator. Any signal can also be monitored on an ink recorder for checking telegraphic signals, or on a facsimile visual recorder in the case of facsimile signals. The facsimile recorder is used for checking outgoing signals from Rocky Point, as well as incoming facsimile signals from London and Berlin. Due to the very high speed at which facsimile signals key the transmitter, the visual recorder is especially necessary for checking the adjustment of both the receivers and transmitters.

The principle of diversity reception has also been applied to telephony. The problem of bringing together the outputs of several antennas in such manner as to be independent of phase, is more difficult in the case of telephony than in the case of telegraphy, because of the higher modulation frequencies involved. That is, it has been found that different frequencies not only fade differently, but the phase relations between the various frequencies is often continually varying due to changes in the transmission medium. One would expect that the random changes in phase relations would increase for increasing differences in frequency, and this has been found to be generally true during disturbed conditions. Consequently, the telephonic currents received from one antenna are likely not to have any definite phase relations with respect to the currents received from a similar antenna spaced some distance away, and little is to be gained by adding the outputs of two or more receivers together during times when the fading is most severe.

In general, however, it has been found that, at any moment, the antenna with the greatest signal strength may be expected to deliver the best quality at the output of the receiver. A simple arrangement has been devised which serves to select automatically the receiver having the strongest signal. In this arrangement, three spaced antennas associated with three separate receivers, are used. The signal outputs from each antenna pass through separate superheterodyne receivers to the grids of individual second detectors. The plate circuits of these second detectors are energized by one battery feeding current through a load resistor common to all. This load resistor is connected between the negative end of the plate supply battery and ground. The audio frequency output is taken from across this load resistor. The voltage drop across this resistor is also applied, through a time constant circuit, to the control grid bias of the high-frequency amplifier tubes of all sets, thus affecting automatic volume control of all receivers simultaneously.

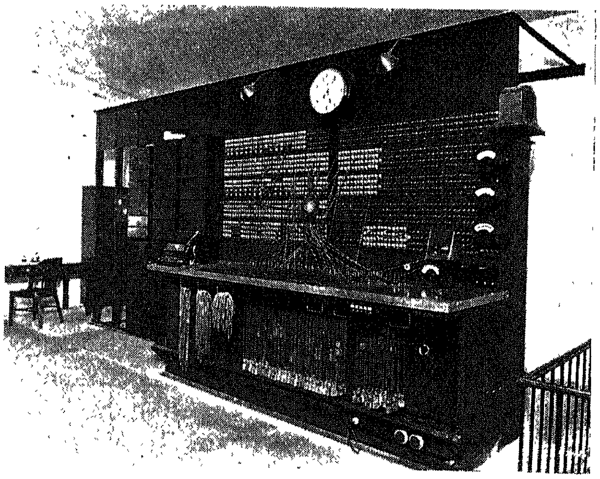

FIG. 16—WIRE LINE CONTROL BOARD IN RECEIVING STATION, RIVERHEAD, N. Y.

The second detectors are operated with the grids biased considerably negative, so that the output is approximately proportional to the square of the input voltage. Consequently, the detector having the greatest input will contribute most of the combined output. Thus, if the signal on one antenna is twice as strong as on another, its receiver will contribute four times as much to the combined output as will the others. Consequently, as the signal carriers fade up and down in a random manner at the several spaced antennas, the receiver with the strongest carrier reduces the output from the other receivers, and, in this manner, an effective switching action is produced. The time-constant circuit may be adjusted to operate at any desired rate in order to handle different classes of fading.

The diversity telephone receiver just described has been used for some time at Riverhead, L. I.; Point Reyes, California; and Koko Head, Territory of Hawaii, for handling addressed program material for international broadcast purposes. Many of these programs have been put on the coast to coast networks of the National Broadcasting Company and the Columbia Broadcasting Company during the past two years.[12]

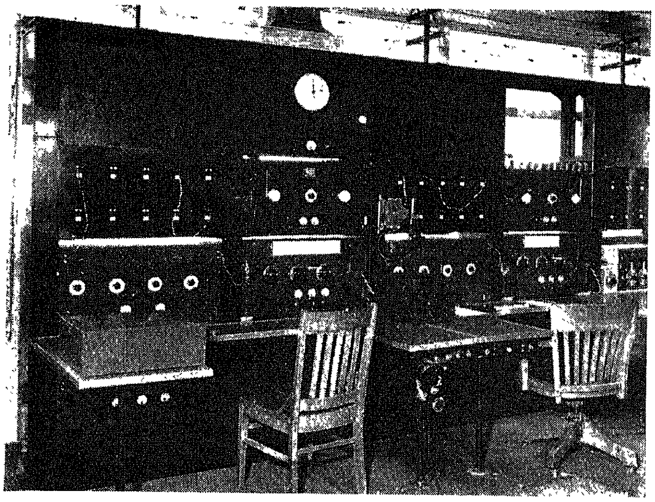

Fig. 17—A Portion of the Frequency Measuring Laboratory, Riverhead, N. Y.

### Frequency Measuring

With the increasing necessity for operation of channels within narrow limits of frequency tolerance, it has become essential to have apparatus set up for accurately measuring the frequency of any given radio signal. Precision apparatus is now set up at Riverhead, N. Y.; Rocky Point, N. Y.; and Point Reyes, California, for making such measurements. (Fig. 17) The measurements are made by a process of direct comparison with the harmonics of a base frequency of 100 kc. generated by a crystal controlled oscillator of high stability. The local standard is known to be accurate to considerably better than one part in one million and the observational errors are made negligibly small.[11]

At Riverhead an average of approximately six thousand measurements per month are made with two operator's positions. Not only have these measurements been found very useful in supervising the performance of our transmitters, even as distant as Manila, but they have been indispensable in resolving such cases of interference as occur on our various circuits by providing ready and reliable information as to the stations involved. This is available not only as of the time the interference is experienced, but, also from thousands of routine measurements which are regularly taken and supplied to the R.C.A. Central Frequency Bureau. At the Frequency Bureau, continuous records are maintained of the history and performance of more than a thousand active high-frequency stations throughout the world. Records are also kept of the frequencies on which some 5,000 additional stations are projected or are occasionally measured.

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# Radiotelephone Experiments Over Short Distances

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Associate, A.I.E.E.

*Synopsis.—The paper describes radiotelephone experiments that have been carried out over comparatively short distances on the North Pacific Coast during the last three years, employing equipment that has primarily been developed for Air Transport Communication. Commercial operation extending over a year has proved the feasibility of such a service where physical plant is economically impossible.*

* * * * *

RADIO is proving to be an effective means for the establishment of world wide telephone communication, because it furnishes a ready method of spanning the natural barriers over which wires either cannot be placed or can be placed with so great a difficulty as not to be economically justified. The usual application of radiotelephony is to connect the telephone networks of one continent to that of another by bridging a large intervening distance. Generally speaking, on the North American Continent at present there are very few communities of any appreciable size that are without telephone connection to the outside world. Exceptions to the above are to be found on the Pacific coast in British Columbia and Alaska where the intervening distances, although comparatively short, are of such a rugged nature as to render the use of the usual physical plant impossible from a cost standpoint.

During the year 1929, the British Columbia Telephone Company decided to attempt telephone linking of isolated communities to the north by means of radio, and at that time the pulp and paper town of Powell River, Fig. 1, was chosen for connection with Campbell River, the most northerly point reached by the British Columbia Telephone Company. It will be noted by referring to the map, Fig. 2, that telephone facilities extend from Vancouver northward by means of 32 miles of submarine cable to Nanaimo, located on Vancouver Island, and 100 miles of aerial copper to Campbell River. As far as the mainland is concerned, in a northerly direction plant does not exist beyond the immediate vicinity of Vancouver.

Powell River, nearly 40 miles distant from Campbell River, has a population of 6,000 people and was isolated as far as roads and telephone communication to the outside was concerned. An experimental radio circuit utilizing ground wave transmission was operated satisfactorily on a commercial basis for over a year. The circuit was similar to that later described with the exception that transmitters rated at 50 watts were employed, Fig. 3.

Experimental work carried on while the Campbell River-Powell River circuit was in operation indicated that reliable ground-wave transmission with 50 watts of power was not possible beyond a water distance of approximately 50 miles.

About this time much improved equipment, primarily developed for air transport communication,† became available, and this fact along with the participation and cooperation of the Northern Electric Company of Canada, made additional experimental work on a larger scale possible.

Two 400-watt aeronautical ground transmitters were secured. One was installed at a point 12 miles from Vancouver, on Lulu Island, while the second was placed on the motor yacht *Belmont*.

FIG. 1—PULP AND PAPER TOWN OF POWELL RIVER VIEWED FROM THE AIR

The transmitter consists essentially of a temperature controlled quartz crystal controlling a five-watt tube. A second five-watt tube is employed as a frequency doubler, and its output is amplified by a fifty-watt stage, which in turn operates into a single air-cooled tube rated at one kilowatt for the final stage. Incoming voice energy is applied to the grids of three fifty-watt tubes connected in parallel and modulation takes place in the plate circuit of the fifty-watt radio frequency amplifier. The transmitter has an unmodulated carrier power rating of 400 watts and is capable of complete modulation. Adjustment can be made to any frequency from 1,500 to 6,000 kilocycles. The power supply for the plate circuit of this transmitter is obtained from a three-phase rectifier employing tubes of the hot-cathode mercury-vapor type.

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*British Columbia Telephone Company, Vancouver, B. C.

*Presented at the Pacific Coast Convention of the A.I.E.E., Vancouver, B. C., August 30-September 2, 1932.*

†*Air Transport Communication*, by R. L. Jones and F. M. Ryan, A.I.E.E. TRANSACTIONS 1930, Vol. 49, No. 1.

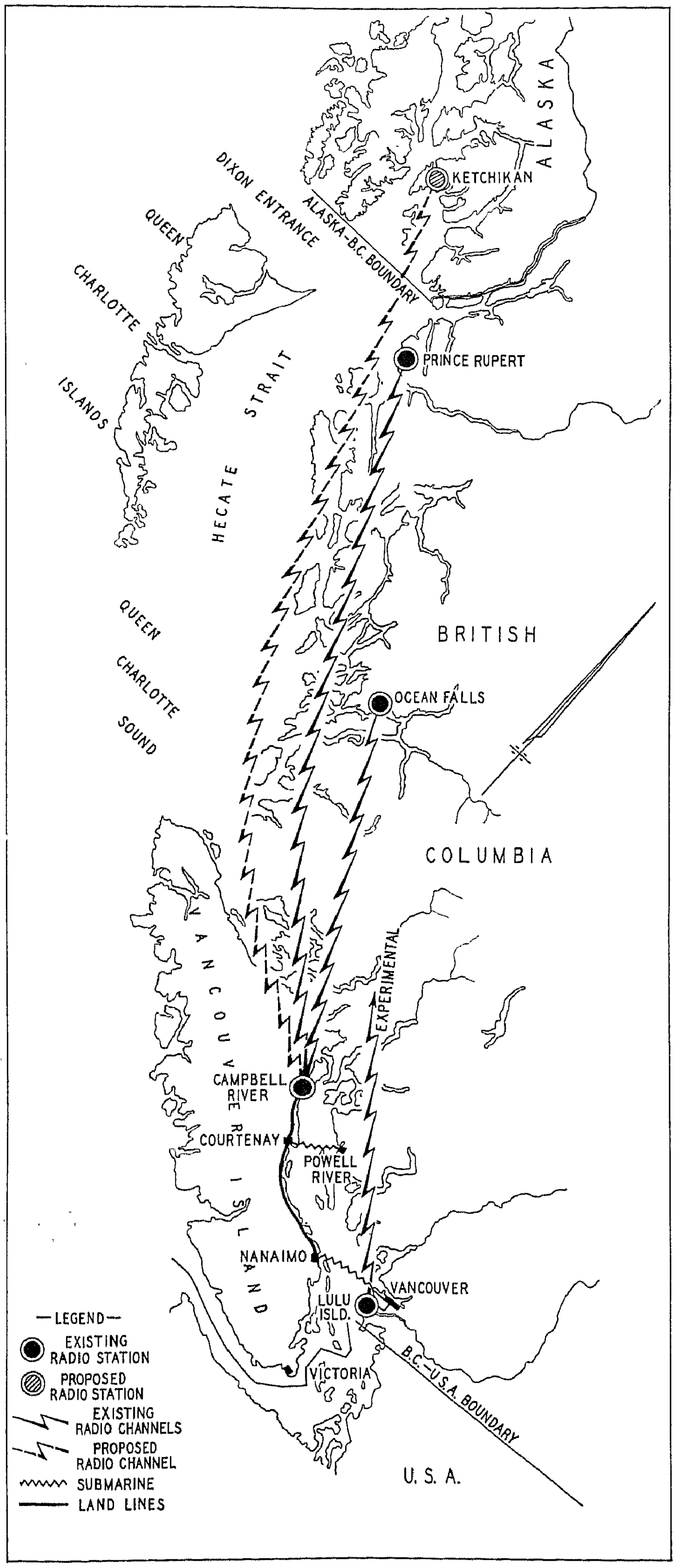

Fig. 2—Map of North Pacific Coast Showing Radio Operations

The *Belmont* is 75 feet in length with accommodation for eleven people. Special masts 50 feet in height were added and a five-kva. full-automatic gasoline-driven alternator* for radio power supply was included.

The Lulu Island station consisted of a small frame building built on a sea wall at the mouth of the Fraser River. Two antenna poles one hundred and fifty feet above ground were erected. A receiver was placed two thousand feet away from the transmitter along the dyke, and terminal equipment installed to permit conversations from the *Belmont* to any telephone reached by the Vancouver long distance telephone operators.

Due to the restricted space on the yacht, it was not possible to arrange for full duplex operation, so a simplex system, similar to that used in aircraft operation, was employed.

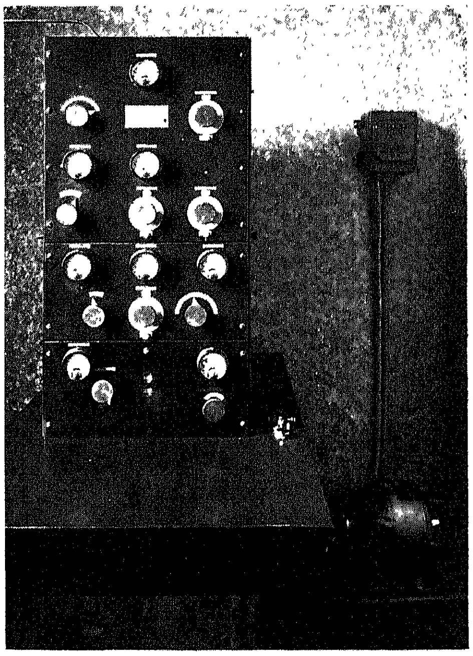

Fig. 3—Campbell River 50-Watt Transmitter

The *Belmont* started out for the north on August 18th, 1930, and tests were continued up to the middle of October. All points of any importance between Vancouver and Ketchikan, Alaska, were visited. The skip effect of various frequencies up to 6,500 kilocycles was studied and field strength measurements were plotted for the various frequencies tested throughout the day and night. Numerous experimental calls were completed from the yacht to various points in the United States and Canada. People in Alaska talked for the first time to Chicago, New York and Montreal via the 600-mile radio circuit from the *Belmont* to Vancouver, thence by land facilities of the American Telephone and Telegraph Company to the east.

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*"Small Alternators Now Fully Automatic," by Earle R. Wetzel, *Electrical Engineering*, January 1931, Vol. 50, No. 1.

The northern trip demonstrated that not only was this type of telephone transmission practicable, but that there was a keen demand for any form of communication that would allow a telephone conversation, even if this service was restricted to a certain portion of the day.

Ocean Falls, a pulp and paper town of approximately 2,500 inhabitants and located three hundred miles north of Vancouver, was selected for the next radiotelephone installation.

The local telephone system was acquired and the 400-watt transmitter at Lulu Island was moved to Ocean Falls and placed in a small frame building one and a half miles from town. The receiver was installed in a second building one-half mile beyond the transmitter. A pole line was built carrying the necessary power and telephone facilities along the only highway. The receiver output and the input to the transmitter are carried by telephone circuits to the telephone office where the terminating and control equipment is placed.

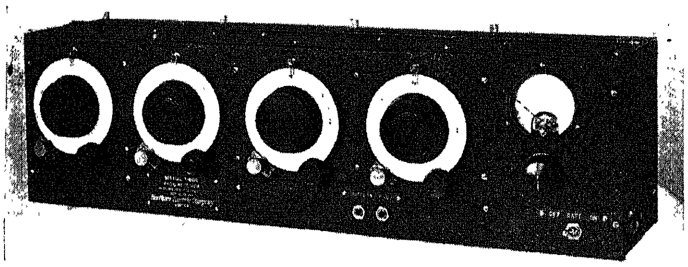

Fig. 4—Special Short-Wave Receiver Equipped with Automatic Gain Control

The transmitter and subsidiary equipment was removed from the *Belmont* and located in the Campbell River telephone office along with one terminal of the Powell River circuit still in operation. High poles similar to those at Lulu Island were erected, and as commercial power was not available, it was necessary to use the gasoline-driven alternator from the yacht.

In the course of the experimental cruise it was soon demonstrated that while the surface or ground-wave component could be relied upon for fairly steady signals, sky wave transmission was extremely erratic. Conditions of fading with the receiver at a remote unattended point resulted in very unstable operation. With average gains strong signals would cause distortion by overloading, while weak signals resulted in low levels. To take care of this condition a specially tuned radio frequency receiver, Fig. 4, with an automatic gain-control circuit was developed. This receiver was arranged to cover frequencies from 1,500 to 6,000 kilocycles and will hold the output signal to approximately ∓ two db. with an incoming radio frequency voltage ranging from 8 to 3,000 microvolts. An output level of + 14 db. is possible for 100 per cent modulation of the radio wave.

It was found extremely important that the receiver site be sufficiently isolated to minimize local interference and with this in mind, the Campbell River receiver was set up in a small frame building approximately three and one-half miles from the telephone office. Another important requirement is that the transmitter be a sufficient distance from settled areas to preclude interference with broadcast reception. At Ocean Falls it was found that a transmitter of appreciable power located in the town, even when sending on a frequency as high as 4,500 kilocycles, was picked up on the older type broadcast receivers. This was

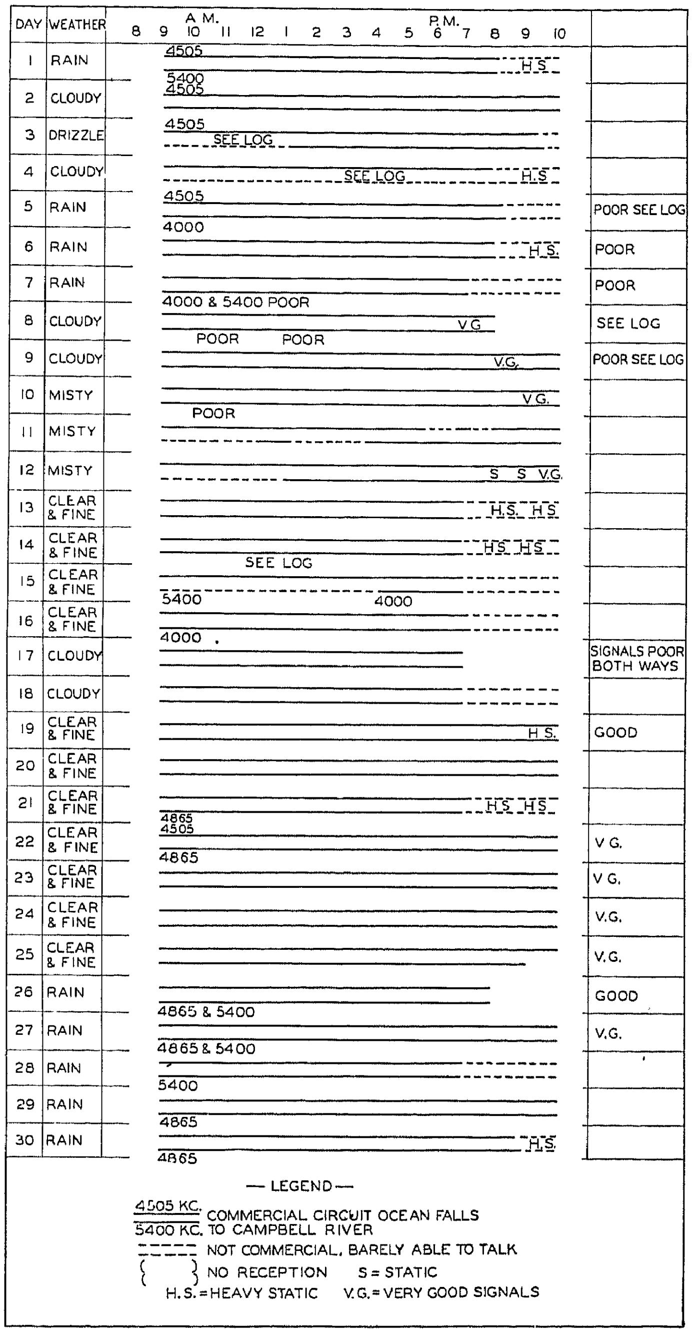

Fig. 5—Campbell River—Ocean Falls Radio Circuit Operation During September 1931

particularly true on operation at night with frequencies between 1,600 and 3,000 kilocycles. Some difficulty was experienced in completely suppressing the quartz crystal frequency which was half the carrier frequency where doubling was used. This unfavorable condition was completely eliminated by the present separation of over a mile from the nearest broadcast receiver and operating without doubling on the lower frequencies.

Tests made at Ocean Falls on the occasion of the *Belmont* cruise indicated that considerable difficulty would be experienced from Ocean Falls in event of commercial operation, due to the proximity of the mountains. Broadcast reception was also very erratic as compared to other points on the coast. In some cases reception could not be experienced at all, and generally speaking, during the summer months was only possible late at night.

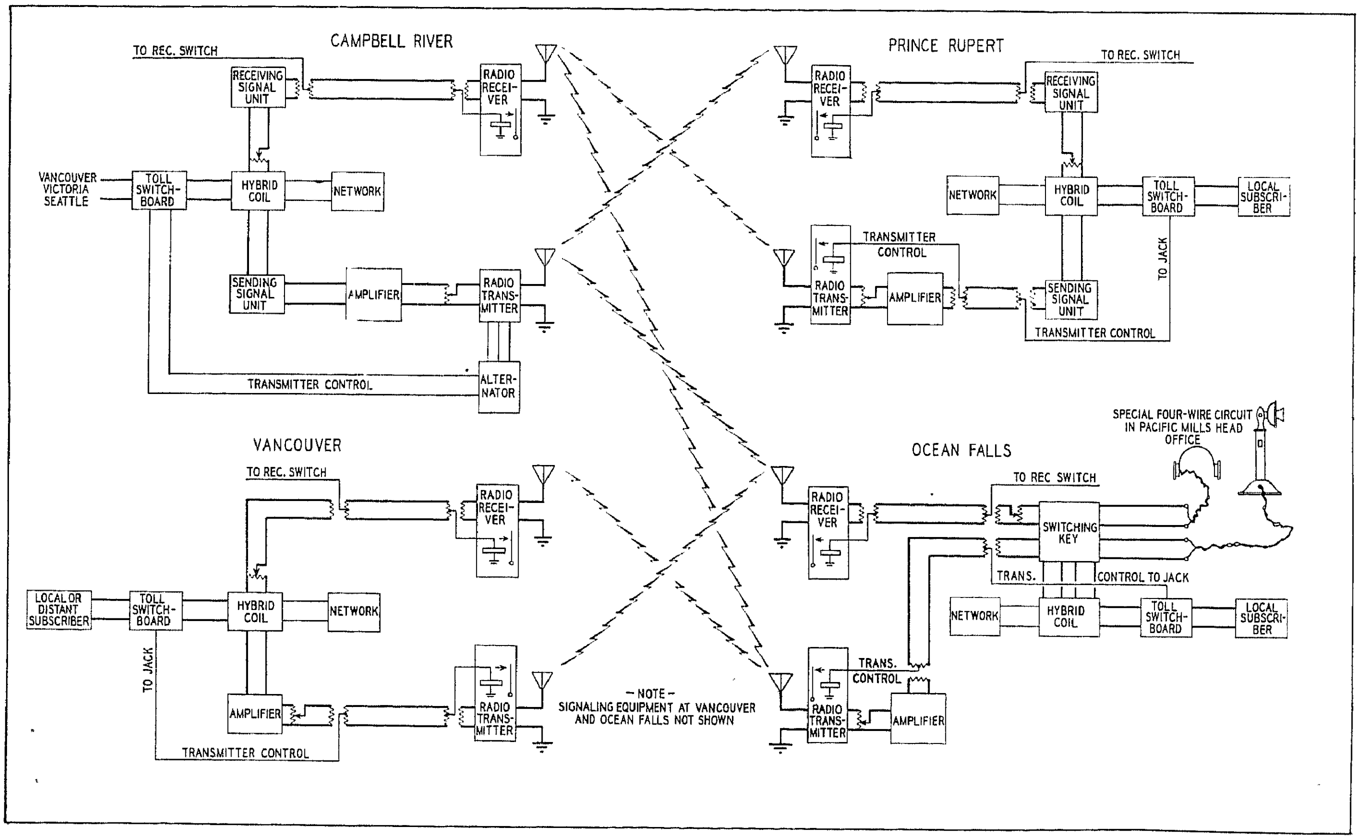

FIG. 6—SIMPLIFIED DIAGRAM SHOWING EQUIPMENT AT VANCOUVER, CAMPBELL RIVER, OCEAN FALLS AND PRINCE RUPERT

The Ocean Falls-Campbell River 210-mile radio link was finally cut into service April 1st, 1931, operating on 4,505 and 4,865 kilocycles respectively. Tests had been conducted on the basis of day and night service with the consequent changing of wave lengths. The night antenna was placed at the top of one hundred and fifty foot poles with the day antenna on the same poles approximately one-quarter wave length above ground. It was found that the amount of business received at night did not justify this change, so initial operation was carried on between the hours of 8 a. m. and 6 p. m. In the winter season the day frequencies are usually not effective after 6 p. m.

During the summer months it was possible to obtain fairly consistent twenty-four hour service on the day frequencies, calls being completed as late as 11 p. m. and as early as 4 a. m.

The Ocean Falls-Campbell River radiotelephone circuit has been in commercial operation for over a year and during this period results have been well above expectations. With few exceptions all business offered was completed, including calls to all parts of the United States and Canada, with as many as forty handled in a single day. The exceptions mentioned were due to land line failures on Vancouver Island, and to severe atmospheric conditions. These atmospheric storms occur about twice a year. During the first day of these phenomena signals are missing entirely, or are so weak as to be useless. Changing wave lengths over a wide range of frequencies does not improve matters. Usually at some period of the day the circuit will be normal long enough to complete any business that is waiting. For several days following, sometimes for a week, the circuit will be extremely erratic, with signals fluctuating over a wide range.

Fig. 5 shows, graphically, operation during the month of September 1931. It will be noted that three different frequencies were used in transmission to Ocean Falls. At this time tests were being conducted on 4,000 kilocycles and 5,400 kilocycles, as well as on the usual 4,865 kilocycles, to determine the optimum frequency for transmission at this time of year. Transient conditions such as fast, slow or selective fading with accompanying distortion are experienced at times, but it is surprising how little this affects a telephone conversation, particularly if the principals involved are experienced in the use of the telephone. Static is very rarely experienced in day operation. The Pacific Mills operating the pulp and paper plant at Ocean Falls transact considerable business by telephone to their head offices in Vancouver and San Francisco. At least one call of not less than twelve minutes duration, and usually close to a half-hour, is placed each day to Vancouver. Since the commencement of service these calls have all been completed with the exception of two occasions when land line failures were experienced.

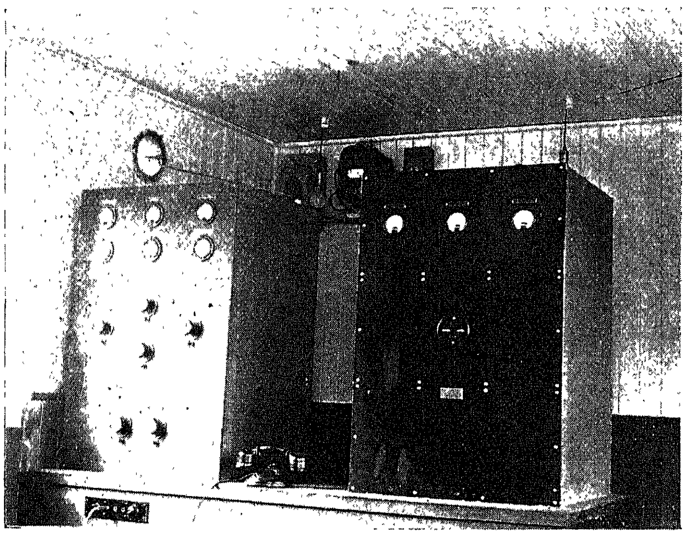

Fig. 7—Prince Rupert Transmitter Installation

In the early stages lack of secrecy was thought to be a serious obstacle, but up to the present no unfavorable reaction has resulted. At some future date it is planned to add secrecy equipment which is now under development for this type of installation. It will be noted from the simplified diagram, Fig. 6, that it is possible to operate the Ocean Falls terminal either with the usual hybrid termination or by straight four-wire. There are advantages in the use of four-wire operation from a secrecy standpoint but the particular advantage is in instances when signals are weak or erratic.

A further addition to the radio network occurred on January 15th last, when the City of Prince Rupert, British Columbia, was connected.

The radio equipment employed and the arrangement is essentially the same as Ocean Falls. Connection is made with Campbell River operating on the same wave length as Ocean Falls. This method of operation is desirable from an economic standpoint until such time as increased business justifies a separate circuit. The local telephone system is owned by the City of Prince Rupert and the radio circuit is terminated on its switchboard. Operating and maintenance is carried out by its regular telephone personnel.

A brief description of the operating procedure is as follows: On receiving a long distance call from a local telephone, the Prince Rupert long distance operator plugs into a jack designated "radio," which automatically starts the transmitter. A delay of seven seconds is required for the tubes to reach a temperature that will allow the safe application of high tension voltage. A red lamp appears in front of the operator when the transmitter is in readiness to receive a call. She then operates a ringing key which actuates a standard telephone ringer of the same type as used on composited telephone lines, thus modulating the transmitter with 135-cycle current. This signal is detected by the Campbell River receiver and operates the tuned 135-cycle portion of the Campbell River ringer, thereby producing an audible signal. The Campbell River operator answers by starting up her transmitter. As it will be remembered that commercial power is not available at Campbell River, the insertion of the plug in the switchboard jack first of all starts the gas-engine-driven alternator, which in turn energizes the transmitter. This added operation increases the interval before the transmitter is on the air by an additional ten seconds. The Campbell River operator then takes the particulars of the call and both transmitters are left running until the call is completed or until the Prince Rupert subscriber receives a report on his call. A call originating in Vancouver would be put through in the same manner by the Campbell River operator.

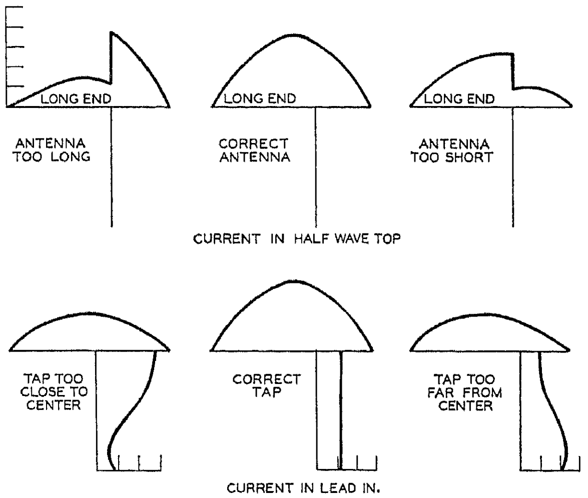

Fig. 8—Antenna Diagrams Showing the Effect of Various Adjustments on the Current Distribution

Although the transmitters at each station run only when business is being carried on over the circuits, the heaters on the quartz crystal frequency controls are on continuously to insure the frequency stability of the transmitters. The receiver, of course, is left on during the hours of operation, and is turned on and off as required by the regular long distance operator from her switchboard position.

To date, operating results experienced on the Prince Rupert circuit have been very good.

Considerable care is exercised in the construction and adjustment of the antenna systems. In all cases a horizontal half-wave Hertz antenna is employed, located approximately one-quarter wave length above ground, and connected to the equipment by a single wire transmission line. Care is taken to terminate the feeder in its characteristic impedance to preclude radiation from the feeder itself. A device consisting of a radio-frequency meter mounted in such a manner as to permit it being readily moved along the flat top or transmission line is used to explore the antenna. Readings are taken throughout the flat top and feeder by the aid of field glasses or a transit and the results plotted. Fig. 8 illustrates the effect of various adjustments.*

This type of antenna has been found to be somewhat directional, and consequently, is placed to take advantage of this directivity. The ground system consists of a network of buried copper wires.

Recently the Lulu Island location has again come into prominence with the placing of a 400-watt transmitter and subsidiary equipment. Tests are progressing with the aim in view of serving certain of the logging operations, canneries and like industries that are scattered along the coast and isolated in many ways, including communication. The connection with mobile stations such as ships or small harbor craft is another possibility. It is very likely that Ocean Falls in the near future will be operated direct to Lulu Island as considerably improved operation is possible for this distance as compared to Campbell River.

There is the probability that some of the cities in Alaska will be tied into the British Columbia network until such time as business justifies a direct circuit to the United States.

In concluding, it will be noted that the radio projects described are all of an experimental nature. Consistent with economy, it is felt that future work including additions to the present circuits will be of a more permanent nature.

Recent improved apparatus developed by the Bell Telephone Laboratories for harbor craft operation and related equipment embracing such features as secrecy, improvements in signaling, voice controlled relays, and the possible use of directional antenna systems, will provide additional means for improving service. The extent of the downward revision in radio equipment costs and the availability of suitable radio channels will govern the degree of expansion in the providing of radiotelephone service to the smaller communities of of the north. Touching on wavelengths, the cooperation of the Department of Marine of the Canadian Government has been of considerable assistance in the experimental work outlined and is worthy of special mention.

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*For a comprehensive review of this subject refer to "Single-Wire Transmission Lines for Short-Wave Antennas," by W. L. Everitt and J. F. Byrne, *Proceedings of I.R.E.*, Vol. 17, No. 10, October 1929.

# 115-Kv. Submarine Cable Crossing of the Columbia River

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DELIVERY of electric energy from the new Ariel Plant of the Inland Power & Light Company on the Lewis River, Washington, to the load center of the Northwestern Electric Company in Portland, Oregon, made necessary the construction of approximately 36 miles of transmission line including a 115-kv. submarine cable circuit crossing the Columbia River. The crossing site is just north of Portland city limits and about one mile west of Vancouver, Washington. The river, one of North America's largest streams, forms the boundary between the states of Oregon and Washington.

At the crossing location, the river is divided by the one-half mile wide Hayden Island, into two channels, the north channel being 3,460 feet in width and the south channel 1,360 feet. Two separate crossings, one across either channel, were therefore required. (See Fig. 1.) These were connected by an H-frame wood pole type transmission line as study had shown this to be more economical than to continue the cable across the island underground.

The selection of 110 kv. (nominal) for the transmission voltage was determined by an economic analysis of costs at various voltages for delivering energy from Ariel and other possible adjacent developments to load centers in the Portland area; also from consideration of interconnected operation with other utilities in the Northwest. This later consideration had a very important bearing upon the problem since all of the other major companies are now operating or contemplate conversion of principal trunk lines to nominal 110-kv. operation. Furthermore, physical interconnections already exist between all of these companies and interconnected operation has been employed for several years past, so the economic advantages to be gained and necessity for planning to meet the increasing demands for interchange capacity have been clearly demonstrated.

Cost comparisons between crossing the river overhead or submarine for the construction program necessary to meet the load and service requirements clearly established the economy of the submarine method. Factors contributing to this result were: the 198-ft. minimum clearance above low water requirement; the flat terrain at the crossing site or anywhere in the vicinity; the small increment cost for a double circuit overhead crossing over a single circuit making construction for two circuits the logical procedure although only one was needed initially; and, the unusual mechanical strength requirements for the overhead construction on account of the occasional very severe ice loading conditions experienced.

Very careful and thorough consideration was given to the idea of trenching of cables in the river bottom in order to provide protection from ship anchors and other forms of external damage. With present river depth at elevation minus 28 ft. (low water at 0) it was decided that the trench would have to be excavated to elevation minus 40 ft. in order to be beneath future ship channel bed as well as out of reach of projecting anchor and dredge cutter heads. Such a trench constructed 7 feet wide on the bottom with walls of 1:3 slope for withstanding river current would cost from $40,000 to $50,000 and with no definite assurance that the trench at right angles to the current could be kept open during laying without additional expenditures for sheet piling or for removing extra sand yardage.

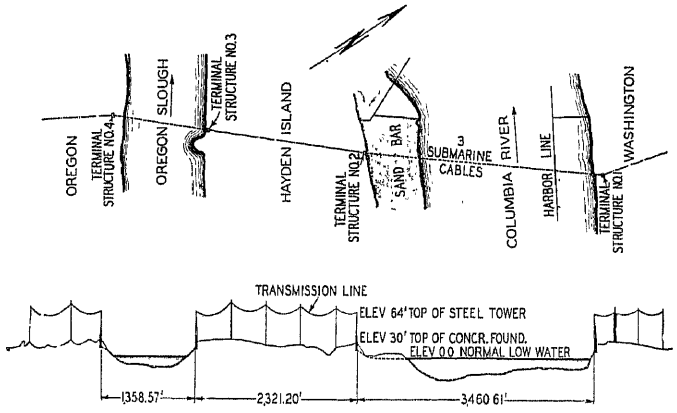

FIG. 1—PLAN AND PROFILE OF CROSSING

With the cables covered in a trench to minus 40 ft. elevation it is believed that it would not be economically practical to salvage the cable in case defects developed. This fact would therefore necessitate the abandonment of that cable and the writing off of a comparatively large investment. With oil-filled cable laid directly on the bed of the river it is believed that the cable can be readily lifted and repaired in case of fault developing. The Northwestern Electric Company has an experience record of 92 submarine cable years covering 11 three-phase 11,000-volt submarine cables laid directly on the beds of the Columbia and Willamette Rivers in the general vicinity of the new crossing. This experience record, excluding pothead failures, discloses only one failure. In that case failure occurred when cable was accidentally picked up by a sand digger clam shell. This favorable experience record, combined with greater accessibility and less chance of abandonment, together with fixed charge savings of from $5,200 to $6,500 per year were responsible for the decision to lay the cable directly on the bed of the river.

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*Northwestern Electric Company.

†General Electric Company.

‡Electric Bond and Share Company.

*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

During the three years study of this problem considerable time was devoted to consideration of the relative merits of cable with solid type of insulation *versus* oil-filled type. The experience and advice of high-voltage cable specialists in several manufacturing and utility organizations throughout the United States was sought and their help is gratefully acknowledged. Final decision to specify oil-filled cable was based on the following facts:

1. Most favorable operating records of oil-filled cable over the past four years, particularly when compared with solid type cable operating at high voltage.
2. High electrical endurance strength of oil-filled cable as demonstrated in laboratory and field tests.
3. Ability of the latter type of cable to maintain perfect impregnation and prevent void formation and ionization.
4. Development of satisfactory joint for oil-filled type submarine cable.

Three cables were laid directly on the bed of the river 4 ft. apart and the shore ends above extreme low water were trenched in and covered with 4 ft. of sand. Some slack in the shore ends was provided for use in case of channel changes by the scouring action of the river or by dredging operations.

## CABLE DESIGN AND MANUFACTURE

The hollow core, single-conductor, oil-filled cable had the following specifications and calculated dimensions:

Inside diameter of copper supporting spiral, 0.690 in.
Inside diameter of conductor strands, 0.790 in.
Outside diameter of conductor strands, 1.277 in.
Conductor cross section, 750,000 cir. mils.
Thickness of wood pulp paper insulation, 0.560 in. (nominal).
Perforated copper shielding tape (0.005 in.) interlocked with one paper tape.
Inside diameter of lead sheath, 2.497 in.
Outside diameter of lead sheath, 2.810 in.
Lead sheath 5/32-in. 2 per cent tin-lead alloy.
Two layers 16 three-ply tarred jute and asphalt.
Hard drawn copper wire armor (0.238 in. diameter).
One layer 16 three-ply tarred jute, asphalt and whiting.
Overall diameter, 3.80 in.
Weight, 20 lb. per ft.
Voltage rating, 115 kv., three-phase, grounded neutral.

Seven reel lengths were manufactured and each length included not only the amount required for installation but also additional cable for test purposes. As manufactured, three lengths were approximately 3,780 ft. each, three more were approximately 1,600 ft. and the remaining 832-ft. length was shipped on a separate reel, to be held in reserve for possible future emergency repair work.

The lead sheath was applied before drying and impregnation treatment. Each length was placed in a steam chamber. Vacuum was applied at each end of the hollow core and drying continued until all moisture was removed. Due to the long lengths involved this drying treatment was necessarily slow, the 3,780-ft. lengths requiring 391 hours. After drying, impregnation was completed with carefully selected, degasified oil having the following characteristics:

Specific gravity, 0.91.
Viscosity at 37.8 deg. cent., 100 (Saybolt).
Pour point, −40 deg. cent.

Following the usual practise the oil in the core, after impregnation was completed, was continuously maintained under positive pressure by use of one or more cell type pressure reservoir units connected to cable end. The first principle of oil-filled cable practise is always to maintain positive oil pressure at all points of cable length in the factory and during shipment, installation and operation. The various operations that are closely followed throughout are solely for the purpose of initially removing air, moisture and other impurities from the entire system, completely filling with oil and maintaining positive oil pressure, so that additional impurities cannot enter through accidental leaks.

After impregnation the cable lengths were subjected to a special volumetric pressure test for assurance that all air and other gases had been removed. The complete lengths (or test samples cut from the ends) were then subjected to various special and standard acceptance tests, chief among which were the following:

1. Factory reel high potential test 166,000 volts, conductor to sheath for 15 min. (60 cycles), before armoring.
2. Dielectric power factor and ionization factor, 20 to 100 volts per mil, 60 cycles, each reel length before and after armoring. Ionization factor limit 0.2 per cent, actual 0 per cent.
3. High-voltage time test. Three 75-ft. lengths, one before and two after armoring. 196,000 volts for 6 hours with 20 per cent voltage steps every 6 hours to failure.

The samples failed at 235 kv. in two, three and five hours.

4. Two 25-ft. samples before armoring for 60-cycle dielectric loss test.

The average measured power factor was: 0.32 per cent at room temperature, 0.27 per cent at 60 deg. cent., 0.28 per cent at 70 deg. cent. and 0.30 per cent at 80 deg. cent.

5. Three 15-ft. samples, two before and one after armoring for bending test.

Four cycles of 180 degree bending at −10 deg. cent. around a mandril 12 times cable diameter. Physical condition noted but electrical tests omitted as meaningless.

After test the seven shipping lengths were as follows: three lengths 3,717 ft. each, three 1,532 ft. each, and one spare 832 ft. length. Each was placed on a separate reel in the body of which was mounted a sufficient number of cell type pressure reservoir units to maintain an oil pressure between 5.0 lb. and 15.0 lb. during shipment and installation. All shipping reel bodies were 7 ft. 2 in. wide. The three reels for 3,717 ft. lengths were 11 ft. 2 in. in diameter and the remaining four had a diameter of 9 ft. 6 in. Each reel was axially mounted in a permanent cradle with band brakes for unreeling cable. Due to excessive size and shipping weight, 45¾ tons for 3,717-ft. units and 21½ tons for 1,532-ft. units, it was necessary to use special gondola freight cars and load only one reel per car. Obviously, such excessive size and weight required special manufacturing facilities throughout and the various operations presented a very interesting and difficult problem.

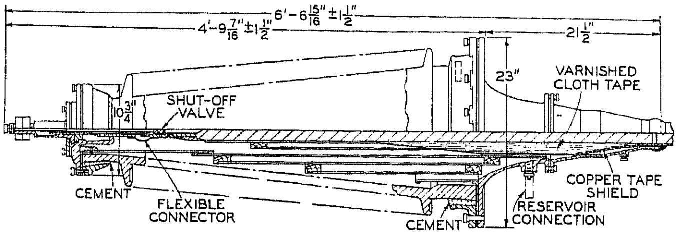

FIG. 2—DETAILS OF 132-KV. TERMINAL FOR OIL-FILLED CABLE

*Carrying Capacity of Cable.* The carrying capacity of a submarine cable, where the same size conductor is used throughout, is determined by the thermal conditions at the shore ends, the temperature rise of immersed section being, of course, much less. The carrying capacity of this particular installation was more difficult to determine than usual because of the relatively short vertical risers at the ends representing the limiting thermal conditions. Due to transfer of heat from these exposed vertical risers into the earth the usual formulas for cable in air do not exactly apply and the thermal correction factor was checked by heat run after installation. On the basis of an ambient air temperature of 40.5 deg. cent., this cable has a conservative rating of 575 amperes for maximum conductor temperature of 70 deg. cent. at vertical risers and with copper armor bonded at base of terminals.

If steel armor had been used under the same conditions, the rating would have been only 430 amperes, due to excessive armor and sheath losses. The advantages of low resistance copper armor in this respect are fully described in a previous publication.[1]

## ACCESSORY DESIGN AND MANUFACTURE

The following accessories and special installation and maintenance treating equipment were also furnished:

*Accessories*

Fourteen single-conductor, outdoor porcelain terminals or potheads.

Six 6-gallon type CC (gravity cell type) oil feeding reservoirs.

Eight 10-gallon type CC reservoirs.

Four 10-gallon type AC (cell type) oil pressure reservoirs for maintaining pressure on emergency oil supply tanks at each terminal.

Eight 50-gallon emergency oil supply tanks with oil level gages, nitrogen gas cylinders, valves, fittings, etc., connected two in parallel at each terminal.

Eight hundred gallons special oil in 50-gallon drums for filling terminal equipment after assembly.

Four valve panels (six valves each) for emergency parallelling or interchange of oil feed for each phase.

Two repair joints with Everdur armor box and clamping rings.

Copper tubing, armored lead piping, valves and miscellaneous fittings for connecting oil system.

*Treating Equipment*

One portable, motor-driven oil degasifier.

One portable, motor-driven vacuum pump.

One impregnating bottle.

Rubber vacuum hose, toggle clamps, tanks of specially dried carbon dioxide and miscellaneous fittings.

The outdoor potheads were rated at 132 kv., following the usual practise of using one size larger porcelain. A cross-sectional drawing of this design is shown in Fig. 2. The guaranteed dry and wet 60-cycle flashover was 375 kv. and 280 kv. respectively and before shipment the potheads were subjected to the following test for leakage: 4 hr. vacuum followed by 2 hr. oil pressure at 80 deg. cent. The terminal lugs had a flexible type stud to allow limited movement of cable conductor during expansion and contraction. There was also a special shut-off valve in the stud so that oil pressure could be maintained in cable core while vacuum treating and filling terminal with degasified oil after assembly.

All reservoir units, piping fittings and other accessories were also subjected to rigid tests for leaks before shipment. They were again tested after installation and then carefully dried, evacuated and filled with degasified oil. The cell type reservoir designs have been described in detail in previous publications.[2,3] One of these[2] also gives a general outline of the principles of oil-filled cable practise and a complete bibliography.

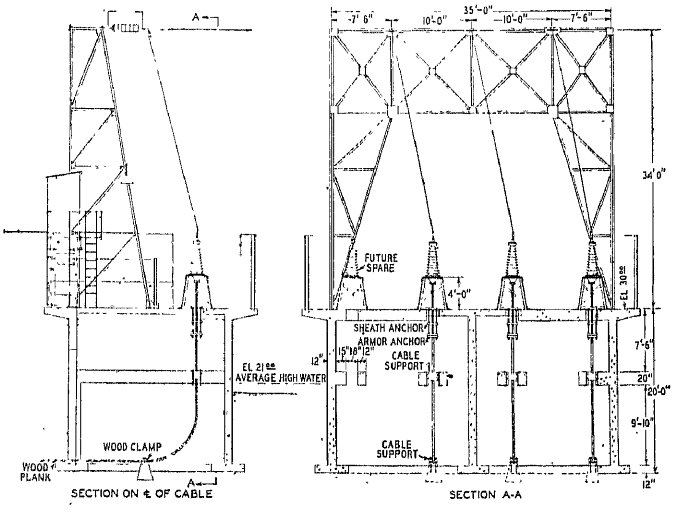

FIG. 3—OUTLINE OF DESIGN FOR TERMINAL STRUCTURES

## DESIGN OF FIELD INSTALLATION

*Terminal Structures.* The terminal structures, four in number, consist of reinforced concrete bases and platforms supporting cable terminals and accessories and steel dead-end structures for the overhead lines. (See Fig. 3.) The decks of these four structures are all

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1. For references see Bibliography.

at the same elevation and are above the usual high water level, but the lower portions will be submerged at high water. The deck of each structure is surrounded by a barrier of steel plate to protect the potheads and accessories from bullets of youthful sportsmen who frequent the neighborhood, and facing the water is a large sign warning against anchorage.

The structure on the Washington side of the main channel has a foundation of wooden piles. This structure is nearer to the water's edge than the others and is adjacent to the ship channel. No piles are used underneath the other structures. Jetties or dykes for protection against undercutting and damage by floating objects during flood periods will be provided for the structures on both sides of the main river channel when deemed necessary.

The steel dead-end overhead structures are mounted on the decks of the concrete terminal structures. They are self-supporting and are designed to withstand maximum expected strain, under heavy ice loading of the 795,000-cir. mil A.C.S.R. overhead conductors. To guard against failure from unforeseen loading conditions each conductor is dead-ended through a shearpin designed to fail at the value corresponding to the maximum safe strain on the structure.

*Anchoring.* Anchoring of the cables is accomplished by the use of two concrete dead-men at each terminal structure. Chains are carried back from these deadmen to the three cables. Attachment to the cables is made by means of basket grips, this attachment being considered sufficient due to the fact that a considerable section of cable between the structures and the water's edge is buried in the sandy river bank, which will take up a considerable amount of pulling tension.

*Bonding and Grounding.* Due to the fact that the cable armor is hard drawn copper some special problems were encountered in the bonding and grounding of this installation. During operation the armor carries a current almost as great as that in the conductor and for this reason carefully designed and installed high capacity bonds are necessary. Careful study of probable electrolysis conditions, including analysis of the river water, indicated that there should be very little corrosion due to electrolysis. The water has a comparatively high sulfate content. If electrolysis does have a tendency to start at any point, the lead sheath soon becomes coated with a tough, permanent film of lead sulfate, thus automatically stopping the action. However, since with copper armor any corrosion which might occur would affect the anodic lead sheath and not the armor, it was considered advisable to take all possible precautions against damage by corrosion. To this end the armor strands of the three cables are bonded together separately from the sheaths, the latter also being bonded together separately and grounded. The two sets of bonds are connected together by a removable jumper, both armor and sheath being grounded when this jumper is in place. The idea of this arrangement is to permit periodically inserting an ammeter between the armor and sheath and testing for electrolysis currents. If appreciable currents should develop the sheath and the armor can then be separated by removing the jumper or they can be connected through a battery supplying a potential counter to the electrolysis potential.

Arrangement of the grounding system is shown in Fig. 4. The ground electrodes consist of a series of driven rods interconnected with each other and with all equipment and structures, forming a low resistance grounding network.

*Lightning Protection.* The lightning protection for the cables and terminals consists of simple spillway gaps mounted across the dead-end insulator strings at each terminal structure. They are well grounded to the grounding network which, in turn, provides a short and effective connection to the cable sheaths. The gap setting for operation at 115 kv. is 30 inches between points, this being considerably below the impulse insulation strength of the cable and terminals and also somewhat below the maximum recommended setting of 36 inches given by the manufacturer of the cable and accessories. It is also somewhat higher than the maximum expected switching surge voltages, so lightning should be the only cause for flashover. Flashover of these gaps may involve a tripout of the transmission circuit in a similar manner to a lightning stroke occurring at any other point of the line.

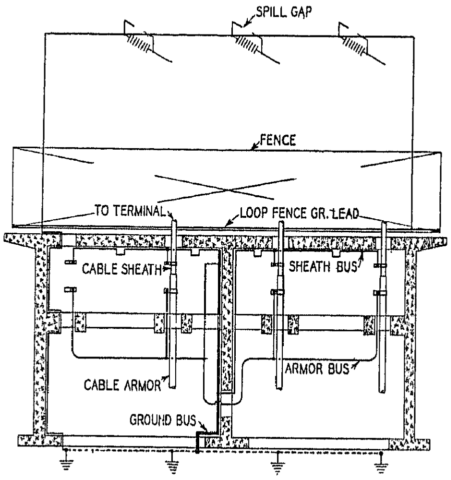

FIG. 4—BONDING AND GROUNDING ARRANGEMENTS AT TERMINAL STRUCTURES

On account of the fog and contamination condition existing along the river, a leakage distance of 80 inches, equivalent to 1.2 inches per kv. to ground, is provided on the terminal bushings. Two strings in yoke each of seven suspension units giving leakage distance of approximately 90 inches are used on the dead ends. No pedestal insulators are required with the simple structure design employed.

*Oil Level Alarm System.* Since the installation is somewhat remote from the nearest attended substation it was considered advisable to provide remote indication of oil level conditions in the oil reservoirs. Such indication is provided by alarm devices at the oil reservoirs, which devices are connected to telephone lines terminating in Vancouver Substation. By a system of resistances, individual indication of the different reservoirs from a given location can be given over a single telephone line, the indications being obtained by an ammeter type of indicator in the station. Only three of the structures are equipped with this signal system, namely the two on the main channel and the one on the north side of Oregon Slough. Fig. 5 is a diagram of this signal system.

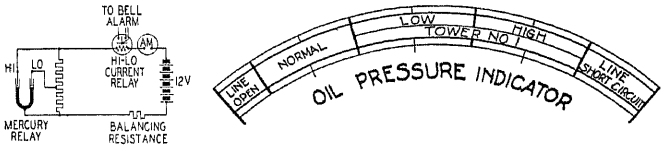

Fig. 5—Oil Pressure Signal System

*Emergency Oil Supply*. Since in case of damage to the cable, resulting in an oil leak, as for instance by ship's anchor, considerable time must elapse before the cable can be raised and the damage repaired, it was considered advisable to provide emergency oil storage so that continuous oil flow can be maintained until repairs can be effected. This emergency storage consists of simple drum type reservoirs, two of 50-gallon capacity each for each terminal structure, with suitable piping and valve arrangement to connect these reservoirs with the cable oil system when needed. The valves are hand operated. These reservoirs are provided with tanks of nitrogen under pressure not normally in contact with oil, but with valve arrangements by which the oil in the tanks can be displaced by the nitrogen under emergency conditions. The contact of nitrogen with the oil for short periods of time is not considered especially objectionable, although contact for longer periods of time would be definitely deleterious. The nitrogen is supplied in ordinary high pressure cylinders fitted with special reducing valves. Safety valves are provided to limit the pressure of the oil when forced by the nitrogen gas from the emergency tanks to the cable oil system. The nitrogen is required to be extra dry and the cylinders are required to be dried out before the nitrogen is introduced. Since it is necessary to avoid contact of the oil in the emergency tanks with air at all times during normal operation these tanks are serviced by small auxiliary reservoirs of the expansible cell type which maintain positive oil pressure in the main tanks at all times. See Fig. 6.

## Oil Pressure and Flow Characteristics

During installation great care was taken to maintain positive oil pressure at all times as a safeguard against accidental leakage and also during periods when cable ends were opened for terminal assembly. Under these conditions a predetermined value of oil flow must be maintained, just sufficient to prevent entrance of moisture or air. During operation the same problem exists and, in the case of submarine cable, the surrounding water pressure at different points of the profile must be considered.

Submarine cable in long lengths presents a more difficult oil feed problem than ordinary underground cable. The limiting conditions are, maintenance of positive oil pressure at middle of cable length during coldest winter weather, without exceeding a safe oil pressure on sheath at low water level under full load summer conditions. The armor gives some support to sheath and the practise is never to exceed a pressure of 20 lb. per square inch at low water level. Water is more dense than oil. There is, approximately, one pound gain in head pressure of water for every 30 ft. of depth, as compared with oil. The head pressure of oil is approximately 2½ ft. per lb.

The Columbia River crossing was particularly difficult because of the great difference (33 ft.) between low and high water levels. The maximum depth in middle of channel at low water level is 30 ft., giving a depth of 66 ft. at high water. After a careful study of conditions it was decided to use gravity feed (type CC) reservoirs mounted at the same level (44 ft. above low water) at both ends and feeding towards middle of cable length. This represented an oil pressure of 18 lb. per square inch on sheath at low water level and left only one or two pounds margin of oil pressure over water pressure at middle of length when load is dropped in the winter at high water level. The margin is sufficient, however, since the assumed conditions are extreme and of only transient nature, pressure drop in cable core lasting for less than an hour after load is dropped.

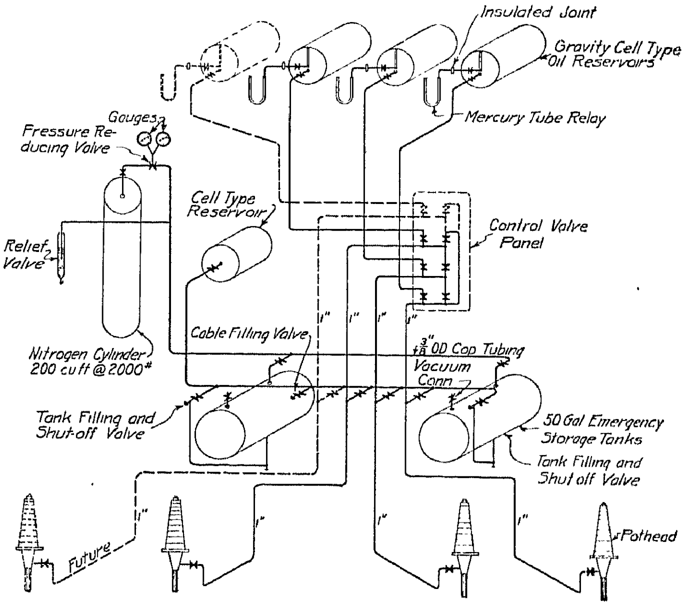

Fig. 6—Oil Piping and Arrangements for Emergency Oil Supply

These limiting conditions, and the need of utilizing all available oil pressure, did not allow the use of restrictors for limiting oil flow in hot weather in case of accident. In the winter such restriction is not needed but in the summer the reservoirs would empty at a fairly rapid rate in case of a "full open" accidental leak in the system.

This question was given careful study. Space does not allow inclusion of details. Briefly summarized the conclusions are:

1. The regular switch signal or the oil level alarm relays will give warning immediately or soon after the accident, allowing an emergency crew to be on the scene within one or two hours.

2. The position of the failure, and other factors, will determine whether the reservoirs involved are exhausted of oil by that time. If not, the emergency oil supply is turned on and the nitrogen gas pressure adjusted (20 lb. limit) to maintain an oil flow not greater than 6 gallons per hr. This will entirely prevent entrance of water or air in the system and the flow can be maintained until the damage is located and repaired.

3. Even if one or more reservoirs is found exhausted the water will enter the cable core very slowly, if at all, and will have traveled only a short distance by the time the crew arrives. Emergency oil flow will then be adjusted as described, the oil leak located and the cable picked up, not at point of leakage, but 200 ft. on each side. It will be cut under oil flow at these points and tested for moisture, repeating the operation in 100-ft. steps if necessary. A length of replacement cable will then be spliced in.

The repair joints, held in stock for such emergency use are of standard design successfully used in previous conduit installations with the exception that the spun copper casing is protected by a cylindrical Everdur armor box, having bolted armor clamps at each end. The cable paper is stepped and the usual low loss varnished cambric tape used for reinforcement wrappings. The halved connector is of the double shut-off plug design that has proved so successful in the past. Copper casing, 3 ft. 8 in. by 6 in. diameter. Armor box, 4 ft. 2½ in. by 8 in.

## INSTALLATION

The importance of this installation, the unusually great size of the reels of cable, and the fact that this was the first submarine installation of oil-filled cable to be made in this country, set a task of a new order for the construction forces, and created many unusual construction problems.

Several weeks before the installation was started, a school was set up for the construction personnel and intensive training was carried out. This included such work as making up pothead connections by the use of short lengths of scrap cable, etc. It was undoubtedly this training together with very careful engineering of the construction work that enabled the installation to be made without serious mishap.

Equipment suitable for laying the long heavy lengths of submarine cable was difficult to assemble from a harbor the size of Portland's, and it was only after considerable effort that necessary equipment at a reasonable rental cost was obtained. This equipment as finally assembled consisted of a flat-decked barge, 400-ton capacity, 125 ft. long, 32 ft. wide, on which the three cable reels for each crossing and control equipment were placed. As auxiliary to the cable barge, a steam dipper dredge barge was utilized as a derrick, and in addition there were two small gasoline donkey scows from the Port of Portland's dredging equipment, a spare flat-deck barge for use as spare deck space, and two small derrick tugs—one for use in changing anchor lines and anchors and one for emergency.

The main barge was arranged for laying the three cables at each crossing simultaneously, the reels being mounted in tandem for proper deck load distribution. The two reels nearest the laying end, or stern of the barge, were raised sufficiently to allow the cable from the reel forward to pass underneath. Easy running rollers were placed at such points as to eliminate all possible friction. An overhanging timber structure was constructed at the stern of the main barge, with rollers arranged for a minimum safe bending radii of cable as it was fed overboard, and which spaced the cables 4 ft. apart. The two flanges of each reel were equipped with friction band brakes, one used for laying control and one for emergency.

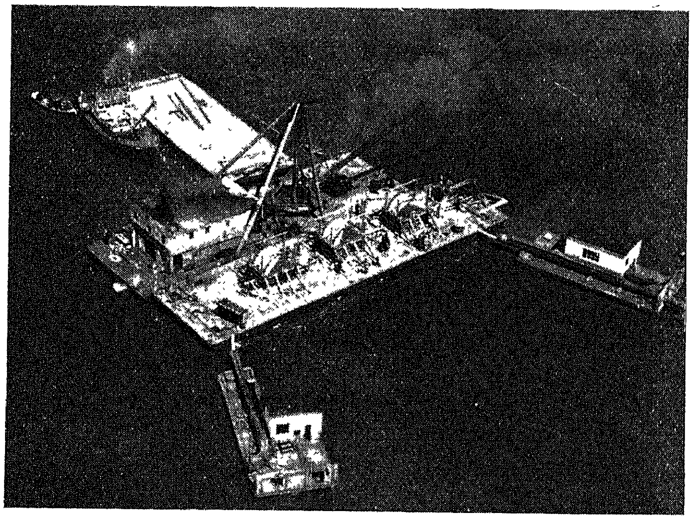

FIG. 7—AEROPLANE VIEW OF EQUIPMENT DURING LAYING OF CABLE

Calculations for running lines and strains were made on the basis of maintaining the main barge when laying the cable sidewise to river current, which at the time of laying was approximately seven miles per hour. A donkey scow was placed at bow and stern on the upstream side of the cable barge. Two steel lines with large anchors attached from each of the donkey scows were maintained upstream while laying and moved in successive steps across the river. The derrick barge was held alongside the main barge on the downstream side, with steel lines from the donkey drums, also with anchors attached, from bow and stern for control of movement across the river. These anchors were also moved as required. The derrick tugs mentioned above were used for changing anchors and to clear lines of driftwood, trees, etc., which were quite heavy at this flood stage of the river. A view of the general arrangement as described above is quite clearly shown in Fig. 7, and the same arrangement is shown diagrammatically in Fig. 8.

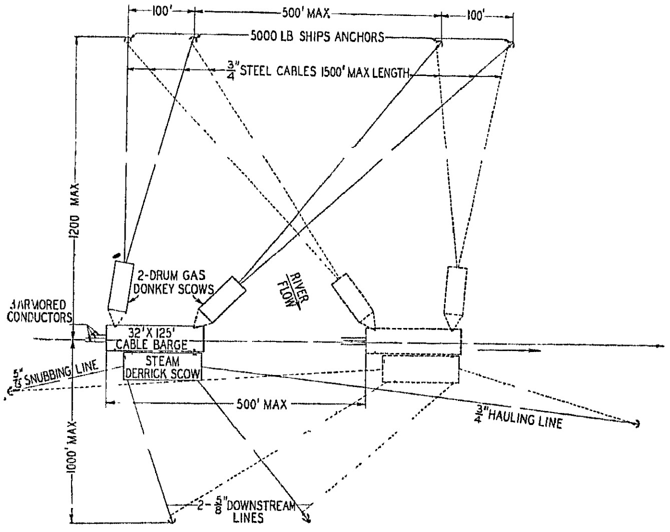

Fig. 8—Diagram of Arrangement of Equipment For Laying Cable

Buzzer and bell signals were provided to each operation control point. One control was from the point where the cable went overboard, controlling slack and reel movement; another point controlled the barge movement across the river and the upstream anchor lines from the donkey scows. This control point was in turn controlled by telephone from the shore where men with transits were located for alinement of the cable across the river.

The shorter sections of cable across the Oregon Slough were laid first, and on a rapidly rising river. For plan of crossing, see Fig. 9. The three shore ends, one at a time, were pulled over rollers, located at frequent intervals, into No. 4 terminal structure by means of lines from derrick hoisting drums, fastened to the armor pulling eyes at the cable ends. (The terminal structures are numbered consecutively from 1 to 4, beginning with the one farthest north.) Cables were then clamped in final position, with necessary slack above terminal pedestals for terminal installation.

Temporary oil connections were made between the three cable ends and the three permanent oil pipings which had been installed with permanent oil reservoirs, emergency oil tanks, etc., previous to cable laying operations. Oil supply to the cable was then made from the permanent oil supply apparatus; oil supply to the cable from the temporary pressure reservoirs shipped with the reels being closed off. Reserve supply of oil and the degasifying equipment were connected and made ready to provide against any possible emergency that might arise. After all connections were complete, short slacks were laid just outside terminal No. 4 and temporarily anchored, and the laying of the Oregon Slough crossing started. This laying to a point approximately 300 ft. from terminal No. 3, where slack was to be dropped, took five hours. Slack, as engineered for this location, was laid out on the deck of the spare barge lashed in place to cross timbers which were later raised with derrick and the spare scow pulled from under the suspended cables. The suspended cables were then carefully lowered to the bottom of the river, later checked as to lay by a diver, and then the lashing cut, allowing timbers to float to surface of river. The laying equipment was then moved to terminal No. 3, the shore end footage of the cable pulled from the reels and placed in the shape of a figure eight on the deck of the spare barge. Reels were then removed from the main barge deck, ends of the three cables pulled into No. 3 terminal, and clamped into proper place. The three cables were then, one at a time, moved over toward the edge of the barge and carefully lowered overboard in final location alongside.

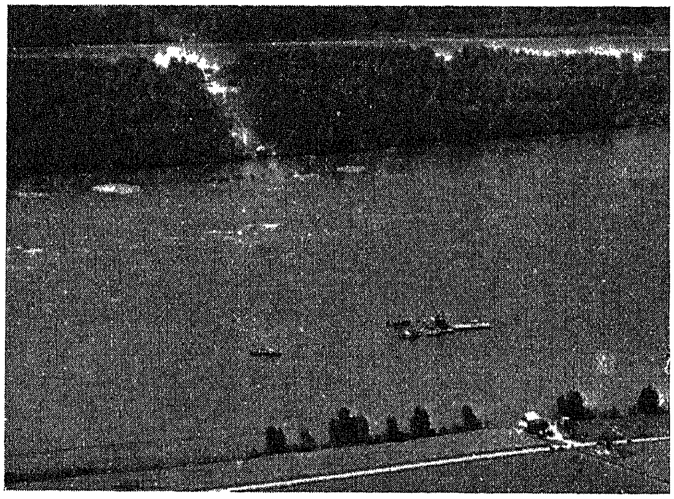

Fig. 9—Aeroplane View of Crossing

Laying of the three longer sections across the main channel was more difficult, on account of the extreme high water and heavy current, but was accomplished in the same manner as the Oregon Slough crossing. Laying of these lengths was started from structure No. 1 on the Washington side of the river and laid to terminal No. 2. The crossing time of the river proper was approximately fourteen hours, the following two days being used in disposing of slack at the outer edge of the

800-ft. sand-bar and working the barge equipment through the dredged channel to structure No. 2.

The same preparations were made at No. 1, where cable ends were first temporarily connected to the permanent oil reservoir system for any oil emergency condition, as were made at No. 4. These preparations were called into use shortly after the laying process started.

When about 1,000 ft. from structure No. 1, the oil pipe connection, between the inner end of the cable and the oil reservoirs contained within the reel body, was sheared off on account of creepage movement of the inner layers of cable. The man handling the emergency oil apparatus at structure No. 1, immediately noticed a drop in oil pressure and, as per instructions, supplied the emergency oil, maintaining the established pressure. Before the crossing of the main channel was complete, the oil connections on the two remaining cables were also sheared off, also owing to the slippage of the inner layers of cable on the reel drum. The leaks thus developed could not be closed off until sufficient cable was taken from the reels to allow access to the inner layer, and at one time it was problematical as to whether there was a sufficient supply of degasified oil available to maintain oil pressure on the cable until oil leakage from broken connections was stopped.

After the cable laying was completed, terminal pothead installation was immediately started at terminal No. 3, the necessary oil flow from cut cable ends being supplied from the permanent oil system through the temporary oil piping at terminal structure No. 4. No difficulty was experienced at any time during installation. The entire structure was temporarily covered with canvas to protect the working deck from rain and, in turn, each terminal location was enclosed with a special tent during taping and terminal assembling operations.

Terminals were next installed at terminal structure No. 4 with oil control for operations at this point through the cable from the permanent oil system at No. 3. The same procedure in rotation was followed for the terminal installation at structures Nos. 2 and 1. In all terminal assembly operations, as well as at other times, telephone communications were maintained between all four structures. This communication between structures allowed very close regulation of required oil flow and pressure during terminal installation and also for the final adjustment and testing of the entire oil system.

Aside from the broken oil connection, no difficulty of any serious nature was experienced during the entire installation of cable and terminals.

As soon as the installation was completed a three-phase, 60-cycle short-circuit current heat run was made, temperatures, induced sheath and armor currents, oil volume changes, etc., being carefully measured. This heat run served a two-fold purpose; it caused uniform dispersion and absorption of any small amounts of impurities that might not have been excluded and it furnished a final check on all theoretical calculations. Table I gives a summary of these calculations and the essential heat run data.

TABLE I—GIVING CALCULATED AND HEAT RUN DATA

| Circulating current (avg.)* | | | 840 ampere load | 795 ampere load |
|---|---|---|---|---|
| | Sheath | Measured | 12.1 per cent | |
| | | Calculated | 11.3 per cent | |
| | Armor | Measured | 90.3 per cent | |
| | | Calculated | 93.2 per cent | |
| Armor temperatures (max.) | | | | |
| Columbia River | | | | |
| | In air | Measured | 28.0 deg. cent. | |
| | | Calculated | 30.1 deg. cent. | |
| | Under water | Measured | | 24.1 deg. cent. |
| Oregon Slough | | | | |
| | In air | Measured | | 30.5 deg. cent. |
| | | Calculated | | 29.7 deg. cent. |
| | Under water | Measured | 25.4 deg. cent. | |
| Oil level in reservoirs | | | At 795 ampere load | At no load |
| Columbia River | | Measured | 8.0 gal | 4.5 gal. |
| | | Calculated | 7.88 gal | 4.2 gal. |
| Oregon Slough | | Measured | 4.8 gal | 2.8 gal. |
| | | Calculated | 4.53 gal | 3.1 gal. |
| Ambient temperatures | | | Columbia River | Oregon Slough |
| Water ambient | | | 15.0 deg. cent. | 16.0 deg. cent. |
| Air ambient | | | 17.0 deg. cent. | 18.0 deg. cent. |

*Percentages given are per cent of ampere load.

## OPERATION

Operation of the cable under normal operating conditions since June 19 to date has been very satisfactory. Cable temperatures and oil level fluctuations have followed the calculated values very closely with varying load conditions.

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2. *Characteristics of Oil-Filled Cable*, by G. B. Shanklin and F. H. Buller, TRANS. A.I.E.E., 1931, p. 1411.
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## Discussion

**Robert J. Wiseman:** The paper brings out an interesting historical fact. It was not many years ago that transmission of power by cables at high voltages was not satisfactory and the utilities complained of limitations placed upon them. The last few years have seen a great change, starting with the single-conductor, 66-kv solid type submarine cable installed by the Philadelphia Electric Company at Wilmington, Delaware. When this Columbia River crossing was proposed and several manufacturers were asked for engineering advice, they did not hesitate to state that it was feasible for 66 kv as originally planned and later when the voltage was raised to 110 kv, again with the engineers of both the Electric Bond & Share Company and the

Northwestern Electric Company proposed an oil-filled type of cable. The writer's company did not hesitate to offer also as an alternate a solid type of cable, believing it practical for this installation.

These recent installations of long length, high-voltage cables should be a source of comfort and encouragement to the utilities in solving their future transmission problems. The cable manufacturers have not only overcome the limitations imposed upon transmission in the past, but also have eliminated the cable as the "neck in the bottle" of best design of a high-voltage, large power transmission system. The manufacturers have spent the time and money for engineering, research, and equipment to meet the utility needs.

Congratulations are due the company which manufactured the cable for this 115-kv installation for the carefulness and thoroughness with which it has carried out the engineering and manufacture; and also to the utility for its confidence in the feasibility of such an installation.

# Thermal Transients and Oil Demands in Cables

BY K. W. MILLER* and F. O. WOLLASTON†
Member, A.I.E.E. Associate, A.I.E.E

***Synopsis.***—*A simple method is given for the precise calculation of temperature variations in underground power cables due to sudden changes in loading. It is shown how the same method is employed for finding the oil demands of oil-filled cables under similar circumstances. A generalization is introduced which permits the temperature variations and oil demands of cables to be readily calculated for load variations of any sort whatever. A method of finding the pressure at any point in the cable insulation at any time is also outlined.*

*The simplified methods eliminate the necessity for a knowledge of higher mathematics and Bessel functions, which would be required in using the fundamental equations. Calculating charts and other devices permit complete solutions to be obtained in less than 20 per cent of the time formerly required.*

* * * * *

## INTRODUCTION

UNDERGROUND power cables almost always operate under variable loading but, because of mathematical difficulties, their temperatures and allowable carrying capacities are usually calculated on the basis of some more or less equivalent steady load. Such approximate methods have been found to be entirely inadequate in so many cases occurring in practise that a precise method has been developed for obtaining the exact temperature and its variation at any point in the cable which will occur at any time due to load changes of any sort whatever. Because the general thermal transient is so basic to all problems of cable rating on a temperature basis, as well as indispensable to a solution of oil flow problems in oil-filled cables, the broad importance and significance of this problem in the design and operation of all insulated power cables is apparent.

It is the purpose of this paper to present the solutions for three problems, namely (a) temperature and oil flow transients for abrupt load changes, (b) the same transients for any general load variation, and (c) radial distribution of oil pressure in the insulation during load changes of either of the preceding types. The completely general solutions of items (b) and (c) have not been published heretofore. Other articles have been published dealing with item (a)[1,4] part of (b),[6] and with longitudinal pressure drops in cable cores and oil feed pipes under various conditions[1,4] and pressure-volume characteristics of oil reservoirs.[1,4,5] Most of these topics are not repeated here. However, this paper presents some short-cut methods and charts by means of which the very complicated and laborious mathematics underlying all these problems have been reduced to a comparatively short application of simple arithmetic and makes the solution easily applicable to temperature problems in cables not of the oil-filled type.

The theory has been independently checked and also verified in every important detail (except for radial pressure drop) by field and laboratory tests which will be referred to from time to time. This being so, mathematical derivations will be relegated to the appendix and the essentials viewed in outline.

The basic assumptions made in the following work are:

1. The problem is initially or can be reduced to one of circular symmetry.
2. The cable conductor has thermal capacity but negligible thermal resistivity.
3. The insulation has both thermal capacity and resistivity.
4. The sheath has thermal capacity, negligible thermal resistivity in its metallic portions, but appreciable thermal resistivity from sheath surface to duct surface.
5. The dielectric power factor is uniform throughout the insulation, and the dielectric loss per unit volume varies as the square of the voltage gradient.
6. The above properties of the cable are constants, that is, they do not vary with temperature or radius.

Most of these assumptions are very nearly true for conditions encountered in practise and are justified by very close agreement between theory and test. Initially duct temperature $T_o$ is also assumed constant and, when this assumption is not justified, an empirical correction must be made.

The superposition principle is completely applicable both for loading (heat sources) and in time, and can be applied with great effect in the development and simplification of the problem. According to this principle, it is permissible to find the solution for unit change in copper, dielectric or sheath loss separately, and then build up the solution for any desired composite load change by proportioning the effects due to each loss and adding. It is also permissible to pass directly from the solution for one abrupt or rectangular load change to two or more successive changes by adding, with proper time sequence, the solution for each rectangular change independently computed. As a final consequence, it allows the Duhamel integral to be applied directly to the rectangular load change solution so that the equations for any general load variation whatever immediately follow almost by inspection.

## SOLUTION FOR RECTANGULAR LOAD CHANGE

The fundamental temperature equation for an abrupt change of load between constant, but different, initial and final loadings is:

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*Director, Utilities Research Commission, Chicago, Ill.

†Street Dept., Commonwealth Edison Company, Chicago, Ill.

1. For numbered references see Bibliography.

*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

$$T = \sum_{n=1}^{n=\infty} e^{-\lambda_n t} C_n F_o(u_n x, K_n) + \frac{W_c'' p}{2\pi} \log R/x + \frac{W_i'' p}{4\pi \log R/r}\left(\log \frac{R}{x}\right)\left(\log \frac{Rx}{r^2}\right) + (W_c'' + W_i'' + W_s'')E + T_o \qquad (10)$$

(For notation, see List of Symbols. For derivations and complete directions for enumerating all equations, see Appendixes I to IV.)

For conductor temperature, $x$ is replaced by $r$, and for sheath temperature by $R$. The component oil demands contributed by shrinkage of the conductor, sheath, and insulation are, respectively:

$$a_1 = (Cc/pq) \sum^{n} u_n^2 e^{-\lambda_n t} C_n F_o(u_n r, K_n) \qquad \textbf{(18)}$$

$$a_2 = (Vv/pq) \sum^{n} u_n^2 e^{-\lambda_n t} C_n F_o(u_n R, K_n) \qquad \textbf{(19)}$$

$$a_3 = (2\pi\epsilon/pq) \sum^{n} e^{-\lambda_n t} C_n [F_1(u_n R, K_n) - F_1(u_n r, K_n)] \qquad \textbf{(20)}$$

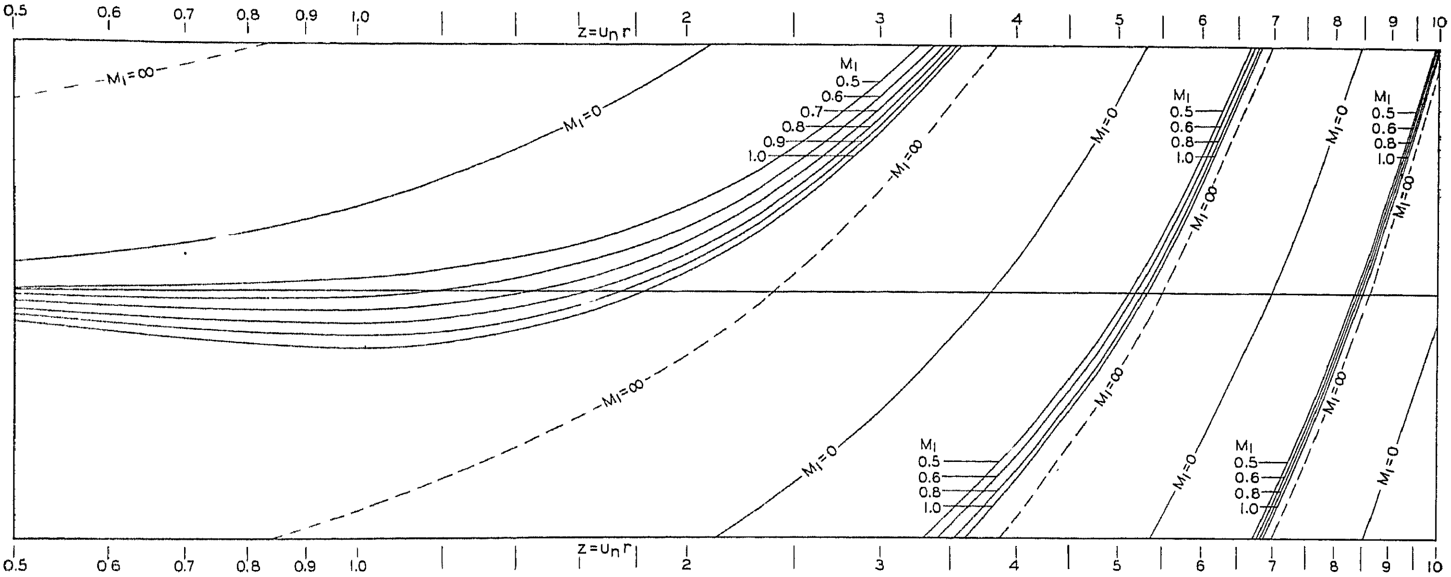


CHART 1

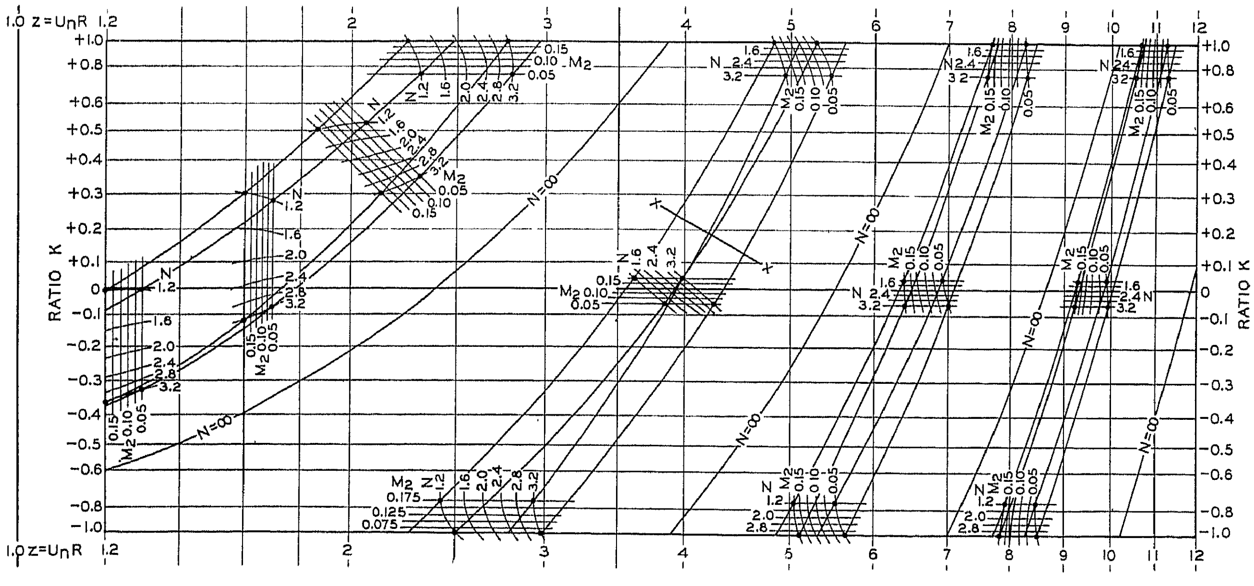


CHART 2

Instructions for Using Charts 1 and 2*

1. Lay Chart 2 over Chart 1 so that the $Z$ axes coincide, and $Z = R/r$ on Chart 2 coincides with $Z = 1$ on Chart 1
2. Interpolate on Chart 1 the sequence of curves for $M_1$, and interpolate on Chart 2 the sequence of curves for $M_2$, $N$
3. Note the points where intersections occur between the interpolated curves of Charts 1 and 2. Three intersections are sufficient
4. For the $n$ points of intersection, read off $K_n$ from the vertical scale. Also read off $Ru_n$ and $ru_n$ from the horizontal scales of Charts 2 and 1 respectively, starting at the left

*In printed copy where Chart 2 is not transparent or removal permitted, it is convenient to trace the $z$ axis, the interpolated $P$ curve for desired value of $M_1$, and sufficient identifying abscissas $z$, from Chart 1, on transparent paper, and to lay this tracing over Chart 2 with proper horizontal shift $R/r$ (to the right), after which intersections may be found as already described and the total oil demand is

$$a = (a_1 - a_2 + a_3)$$

In the foregoing equations, values of $u_n r$, $u_n R$, and $K_n$ are obtained from $n$ successive intersections (three are generally sufficient) of the curves of Charts 1 and 2, which are entered with values of $M_1 = Q_1/2\,\pi q r^2$, $M_2 = Q_2/2\pi q R^2$, $N = p/2\pi E$, and $R/r$. When $x$ is any radius other than $R$ or $r$, then $u_n x$ is obtained by calculation from $u_n R$ or $u_n r$, i. e., $u_n x = (u_n R)\,(x/R)$. The functions $F_o\,(u_n x, K_n)$ are obtained from Chart 3. The functions $F_1\,(u_n x, K_n)$ are obtained from Chart 4. Values of $C_n$ are obtained from the equation:

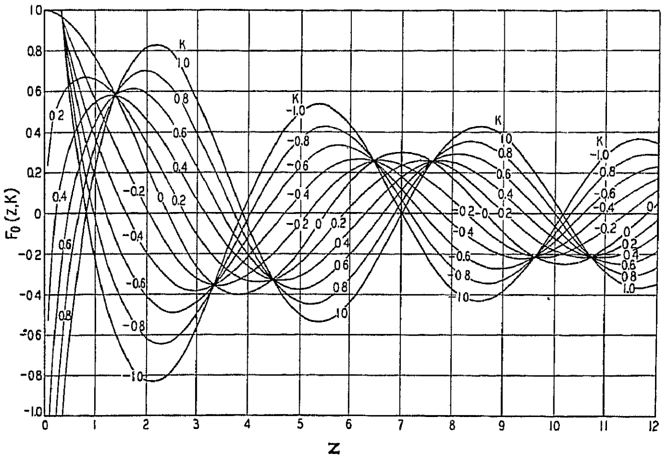


CHART 3—FUNCTION $F_0$

$$\sum_{1}^{n} - C_n F_o\,(u_n x, K_n) = \Delta W_c \frac{p}{2\pi} \log R/x$$

$$+ \Delta W_i \frac{p\,(\log R/x)\,(\log Rx/r^2)}{4\pi \log R/r}$$

$$+ (\Delta W_c + \Delta W_i + \Delta W_s)\,E \qquad (12)$$

by evaluating both sides for $n$ different values of $x$, and solving the resulting simultaneous equations in $C_n$. All quantities, such as $p$, $q$, $R$, $W_c$, $c$, etc., in the expressions for temperature and oil flow transients are readily obtained from Table I, or by well-known methods which require no explanation.

It is best to obtain one set of values of $C_n$ corresponding to unit change in copper loss, another set corresponding to unit change in dielectric loss, and a third set corresponding to unit change in sheath loss. These are used to calculate the temperature or oil flow transients separately for unit changes in each of copper, dielectric, or sheath losses. The transients need be calculated only once for a given cable, since, by the superposition principle, for any particular problem these "unit transients" can be proportioned and added together in any ratio and combination desired, which is the work of but a few minutes.

The oil flows obtained from equations (**18**), (**19**), and (**20**) will be slightly in error for the first few moments of the transient, because only a few terms in the infinite series are used in obtaining numerical values, and the neglected terms are appreciable when $t$ is very small. The following correct expressions should be used for the initial instant ($t = 0$):

$$a_1 = -\,\Delta W_c Cc/Q_1$$
$$a_2 = -\,\Delta W_s Vv/Q_2$$
$$a_3 = -\,\Delta W_i \epsilon/q$$

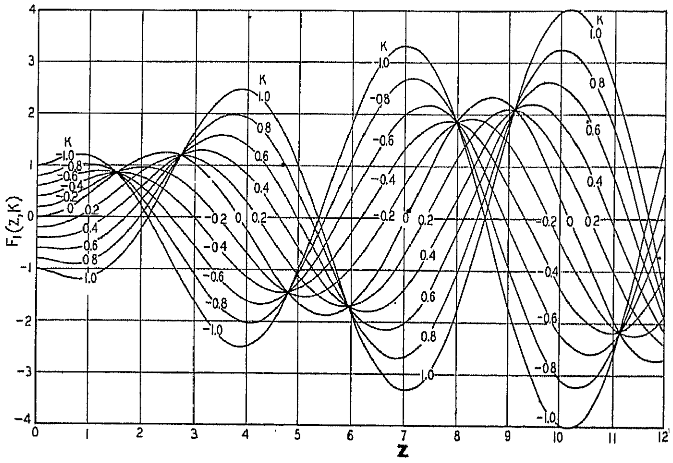


CHART 4—FUNCTION $F_1$

It is apparent that a small discrepancy between measured and calculated values for the initial part of the oil demand curves is not conclusive evidence of void formation in oil-filled cable, as some have maintained.[2,3,4]

## SOLUTION FOR GENERAL LOADING

The transient part of the expressions for temperature variations and oil flows due to rectangular load changes

TABLE I—PROPERTIES OF CABLE MATERIALS

| Material | Specific gravity | Weight lb./cu. in. | Thermal capacity Joules/cu. cm./°C. | Thermal capacity Joules/cu. in./°C. | Thermal capacity Joules/lb./°C | Thermal resistivity °C./watt/cu. cm. |
|---|---|---|---|---|---|---|
| Water | 1.00 | 0.0361 | 4.18 | 68.6 | 1900 | 171 |
| Copper | 8.95 | 0.3230 | 3.44 | 56.4 | 175 | 0.285 |
| Lead | 11.37 | 0.4110 | 1.43 | 23.4 | 57 | 2.990 |
| Transf. oil | 0.90 | 0.0325 | 1.90 | 31.1 | 957 | 611 |
| Dry paper | 1.41 | 0.0508 | 2.26 | 37.1 | 730 | 770 |
| Oil-filled insulation | 1.15 | 0.0415 | 2.10 | 34.5 | 832 | 550 |

The weight of copper conductor is 3.15 lb. and its thermal capacity 551 joules per deg. cent. per circular-inch foot, as ordinarily stranded and cabled.

The weight of lead sheath is 15.5 Dd lb. and its thermal capacity is 883 Dd Joules per deg. cent. per foot, where D and d are the average diameter and thickness in inches.

has been shown to be a rapidly converging, infinite series, each term of which reduces to a constant numerical coefficient multiplied by the simple exponential $e^{-\lambda t}$. For example, the numerical coefficients for use in temperature equations are $C_nF_o(u_nx, K_n)$, where $C_n$ is for unit change in loss. The "unit" results are fitted to a particular problem by multiplying by $\Delta W$, the actual number of units of loss change involved.

The unit coefficients were employed because they can be used directly in the Duhamel integral, a well-known application of the superposition principle by means of which the "rectangular" solution may be readily generalized. For the entirely general load curve of Fig. 12, the general solution for temperature at any point $x$ is:

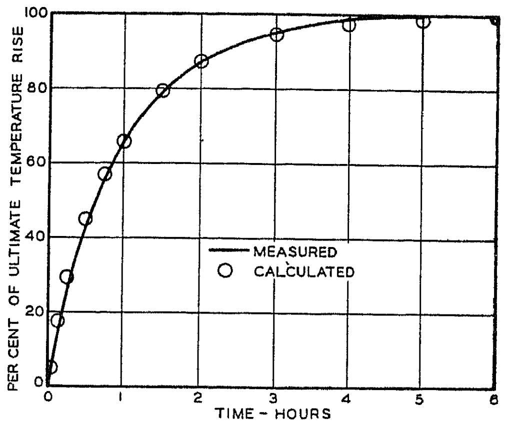


FIG. 1—COPPER TEMPERATURE TRANSIENT DUE TO ABRUPT CHANGE IN COPPER LOSSES

One-conductor 500,000-cir. mil cable having 26/64 in. ordinary insulation and 7/64 in. lead sheath

$$T = \sum^{n} C_nF_o(u_nx, K_n)L_n(W,t) + (W_c)_t \frac{p}{2\pi} \log R/x$$
$$+ (W_i)_t \frac{p}{4\pi \log R/r} (\log R/x)(\log Rx/r^2)$$
$$+ E\,(W_c + W_i + W_s)_t + T_o \qquad (31)$$

The last four terms in the above equation differ from the corresponding "steady state" terms in the rectangular solution only in that instead of using the constant watts loss after the transient, indicated by superscript ($''$), the varying watts loss during the transient, indicated by subscript "$t$," is used, as explained below. The summation term is identical with the corresponding term in the rectangular solution, except that $L_n(W, t)$ is substituted for $e^{-\lambda_n t}$. The load function $L(W, t)$ is known as the Duhamel integral, and for the present purpose is as follows:

$$L_n(W, t) = \left[ \lambda_n e^{-\lambda_n t} \int_0^t (W_t - W_o) e^{\lambda_n t} dt - (W_t - W_o) \right] \qquad (27)$$

The $L$ function consists of two parts, one the instantaneous value of the load $(W_t - W_o)$ at the instant $t$ under consideration, and the other an integral from zero time up to the same instant $t$. Physically one part represents the effect of the load at the time considered, the other part represents the effect of all previous load. From this it follows that the upper limit $t$ on the integral and $t$ in all terms external to the integral are identical.

When the losses $(W)_t$ can be expressed as a mathematical function of $t$, the integral can be formally evaluated. For practical load curves this is seldom the case, and a graphical or a step-by-step method must be employed. For the step-by-step or tabular method the load function is rewritten in approximate form:

$$L(W,t) = \left[ \lambda_n \Delta t\, e^{-\lambda_n t} \sum_{t=0}^{t=t} (W_t - W_o)/e^{-\lambda_n t} - (W_t - W_o) \right]$$

The expression under the summation sign is to be evaluated point by point up to time $t$ (or to point $B$, Fig. 12), using equal finite intervals of time $\Delta t$ for the preceding period. For good accuracy $\lambda_n \Delta t$ should not exceed 0.5 and it is best to use the average values of $W_t$ and $t$ for each increment term under the summation sign. $\lambda_n$ is exactly the same as for the rectangular solution. A complete numerical example of the evaluation of a load function is given in Appendix IV, Table IV.

At the instant of an abrupt discontinuity in $(W)_t$, the values of $L(W, t)$ for use in temperature equations are:

$$\Delta L_{cn} = -\Delta W_c$$
$$\Delta L_{in} = -\Delta W_i$$
$$\Delta L_{sn} = -\Delta W_s$$

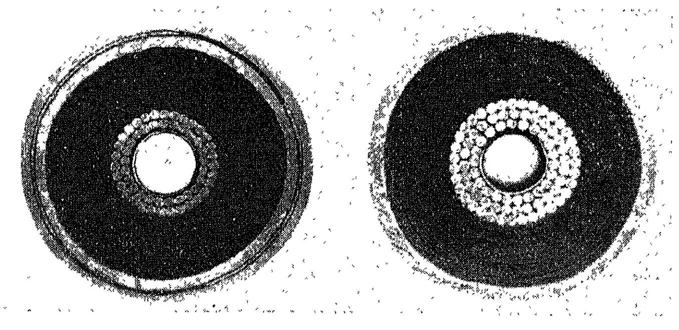

Cable for line 7401 Cable for line 7406

FIG. 2—OIL-FILLED CABLES USED FOR NORTHWEST-DEVON 132-KV. LINES IN CHICAGO

and for oil flow equations, the correct values of oil flow are calculated directly from:

$$\Delta a_1 = -\Delta W_c Cc/Q_1$$
$$\Delta a_2 = -\Delta W_s Vv/Q_2$$
$$\Delta a_3 = -\Delta W_i \epsilon/q$$

for the same reasons discussed in connection with the solution for rectangular load change.

One load function $L_n(W, t)$ is required for every coefficient $C_n$ employed in the rectangular solution. For the complete solution, nine load functions are required, one for each of the three series terms used for each of the three losses, copper, dielectric, and sheath. Of course, when sheath and conductor losses are proportional, the resulting load functions are proportional. Any temperature or oil demand transient corresponding to any general load variation may be found by multiplying the load functions by the appropriate unit coefficients (determined from the rectangular solution), and summing. All the complete equations for general temperatures and oil flows are given in Appendix II.

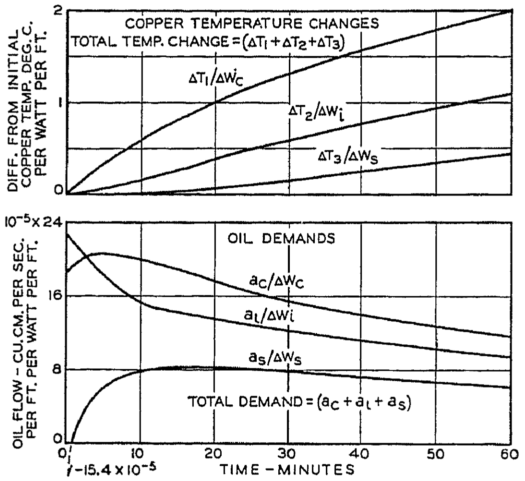


FIG. 3—TEMPERATURE AND OIL FLOW TRANSIENTS FOR CABLE OF LINE 7401, DUE TO UNIT CHANGES IN LOSSES

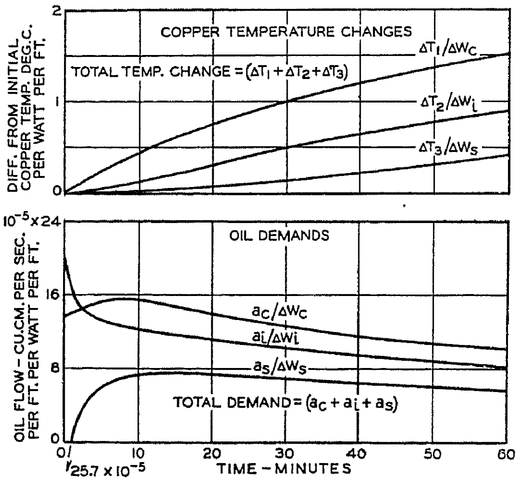


FIG. 4—TEMPERATURE AND OIL FLOW TRANSIENTS FOR CABLE OF LINE 7406, DUE TO UNIT CHANGES IN LOSSES

It is interesting to observe that the final solution for general load variation is based on assuming that a steady load $W_o$ precedes the load variations in which one is interested. (See Fig. 12.) This would seldom be the case, but a start must be made somewhere, and a good approximation is obtained by taking $W_o$ equal to the average load over the period preceding the interval to be investigated. Incidentally, it may be remarked that, if sufficient time is allowed to elapse, the effects of past load changes always shrink into insignificance. Hence, any initial conditions whatever may be selected, provided the start is made sufficiently long before the time at which correct results are desired.

Typical load functions and corresponding temperatures for various time exponentials are shown in Fig. 6. It will be noted that the load function displays all the required characteristics. This seems to be an ideally simple solution for such a complicated problem involving the general space-time thermal transient for a three-component load, each part of which may vary in any arbitrary manner whatever.

## VERIFICATION BY FIELD AND LABORATORY TESTS

The curve of Fig. 1 was selected at random from the results of a series of laboratory temperature tests made at the University of Wisconsin[7] on various cables. The calculated points are shown by the circles. The agreement between calculated and test values for this case of rectangular load change is almost perfect except for the latter part of the transient. The disagreement is due to the fact that, in the test, the heating current was kept constant. This resulted in a continuous slight increase in the conductor losses, due to increases in copper resistance resulting from the rising conductor temperature. The calculations, however, are based on the assumption that the conductor loss remains constant after the transient is initiated. The last few calculated points, therefore, fall slightly below the test points.

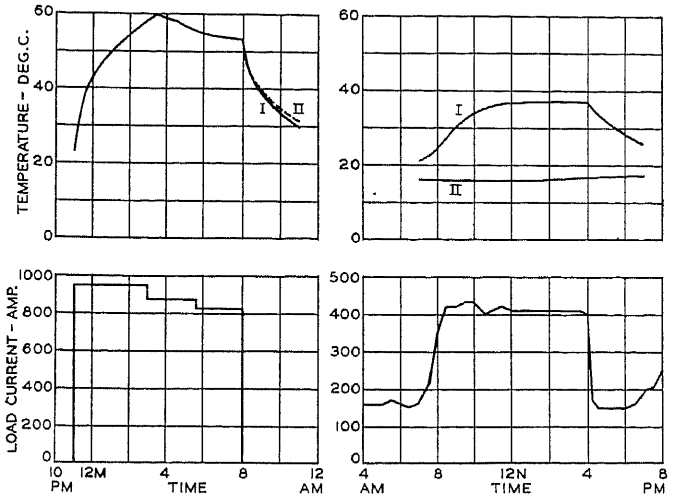
Heat runs which were conducted in Chicago on the two Northwest-Devon 132-kv. oil-filled lines Nos. 7401 and 7406 have provided further verification of the theoretical work. Complete agreement between calculated and test results could not be expected for two main reasons:

1. Duct conditions varied considerably from manhole to manhole along the line.
2. The measured rates of oil flow were determined from oil volume-time measurements on each phase. The changing oil volumes could not be measured precisely due to the nature of the oil reservoirs.

In the check calculations, some of the work concerned longitudinal pressure drops in cable cores and oil feed pipes under various conditions, and pressure-volume characteristics of oil reservoirs. Much of the underlying theory has been developed and published by others,[1,3,4] and is not given here.

The cables of the two lines which were tested are shown in Fig. 2. Line 7401 is made up of 600,000-cir. mil, single-conductor, oil-filled cable having 0.72-inch insulation, 0.69-inch hollow core, and a double reinforced sheath. Sheath losses are present, the ratio of sheath to copper losses being about 1:1. The line is divided into six one-mile sections, fed by gravity reservoirs at one end. A fairly thick oil (G. E. 118) is used. Line 7406 is made up of 1,100,000-cir. mil cable with a single lead alloy sheath. Sheath losses are eliminated. The oil used (G. E. 5314) is thinner than for line 7401. In addition to six one-mile gravity-fed sections, there is one-half mile balanced pressure section. Most of the gravity-fed sections of both lines have booster pressure reservoirs at the far end, which were disconnected during the tests.

The calculated unit temperature and oil flow transients for the two lines are shown in Figs. 3 and 4. The load variations used during the tests are shown in Fig. 5, with the corresponding calculated copper temperatures. During one part of the test on line 7406, the copper temperature was carefully measured by the copper-resistance method. The measured and calculated values agree almost exactly for the first two hours.



Line 7406—First test
I—Calculated copper temperature
II—Measured copper temperature

Line 7401
I—Calculated copper temperature
II—Measured duct temperature

FIG. 5—TEST CURRENTS AND CABLE TEMPERATURES DURING HEAT RUNS ON NORTHWEST-DEVON 132-KV. CABLES

At the end of the third hour, the calculated temperature shows a tendency to decrease more rapidly than it should. This probably indicates that some of the assumed constants of the cable are not perfectly correct. More accurate experimental values are needed for the temperature coefficient of expansion of oil-filled insulation, specific heat capacity of insulation, and other similar constants. It may not be out of place to point out here that most of the so-called thermal constants are only relatively constant. Usually they will be found to vary appreciably with temperature.

A comparison of the theoretical maximum rates of oil flow and the corresponding measured values are given in Table II. The agreement is fairly good, and it is probable that most of the error is in the measured values, due to the difficulty in getting accurate oil volume measurements.

From the calculated oil demands, and the oil viscosities corresponding to the calculated copper temperatures, the maximum and minimum pressures occurring in the cable core were calculated. Only sections on which the boosters were disconnected were considered, since the theoretical complications introduced by the presence of boosters would render such sections unsatisfactory for check purposes. The calculated and measured pressures are given in Table III, and the agreement is seen to be remarkably good.

The theory has provided a complete reconstruction of transient conditions on these two widely different oil-filled cables. The agreement with measured values is excellent, even under the difficult conditions associated with field tests on actual lines.

## PRESSURE DISTRIBUTION IN INSULATION

The principal object or purpose of oil-filled cable is the prevention of free gas spaces or open voids in the insulation. One of the chief causes of formation of such voids is the thermal shrinkage of the oil during decreases in cable loading. With the complete solution of the thermal transient available, a thorough investigation can be made of the possibility of this happening from an oil pressure standpoint for any assumed load conditions.

The pressure drop across the wall of insulation depends on the resistance of the paper tapes to radial oil flow. The insulation of commercial cables is often arranged in zones, the density of the paper tapes being different for each zone. It is necessary to know the dimensions of these zones, and their respective coefficients of friction to radial oil flow. Actual values for the latter have been found to range from 50 to 500 near the sheath, and 400 to 1,000 near the conductor, the

TABLE II—COMPARISON OF MEASURED AND CALCULATED MAXIMUM RATES OF OIL FLOW DURING HEAT RUNS ON NORTHWEST-DEVON, 132-KV. CABLES

| Line 7401 | | | | Line 7406 | | | |
|---|---|---|---|---|---|---|---|
| Load-amps. | | Max. rate of flow gal. per hr. | | Load-amps. | | Max. rate of flow gal. per hr. | |
| Initial | Final | Measured* | Calc. | Initial | Final | Measured† | Calc. |
| | | | | First test: | | | |
| 160 | 420 | $6.6x10^{-4}$ | $7.2x10^{-4}$ | 0 | 950 | $12.7x10^{-4}$ | $13.1x10^{-4}$ |
| 400 | 150 | $7.3x10^{-4}$ | $7.0x10^{-4}$ | 830 | 0 | $11.3x10^{-4}$ | $11.2x10^{-4}$ |
| | | | | Second test: | | | |
| | | | | 0 | 800 | $7.1x10^{-4}$ | $9.3x10^{-4}$ |
| | | | | 800 | 0 | $8.2x10^{-4}$ | $10.4x10^{-4}$ |

*Average value for 6 sections.
†Average value for 3 to 6 sections.

TABLE III—COMPARISON OF MEASURED AND CALCULATED OIL PRESSURES IN CABLE CORES DURING HEAT RUNS ON NORTHWEST-DEVON, 132-KV. CABLES

| | Line 7401<br>Oil pressure-lb. per sq. in. | | | | Line 7406 (second test)<br>Oil pressure-lb. per sq. in. | | | |
|---|---|---|---|---|---|---|---|---|
| | Maximum | | Minimum | | Maximum | | Minimum | |
| Sec. No. | Meas. | Calc. | Meas. | Calc. | Meas. | Calc. | Meas. | Calc. |
| 1 | 28.5 | 29.4 | 15.5 | 14.4 | | | | |
| 2 | 26.0 | 26.0 | 12.0 | 11.4 | | | | |
| 3 | 25.0 | 24.4 | 13.0 | 12.6 | 20.5 | 19.2 | 8.0 | 7.3 |
| 4 | 26.0 | 24.1 | 15.0 | 14.0 | 20.0 | 19.5 | 8.0 | 6.2 |
| 5 | 26.0* | 25.0 | 13.0 | 12.5 | | | | |
| 6 | 38.0* | 37.9 | 16.0 | 16.8 | 10.0† | 8.6 | 2.0 | 2.1 |

*Estimated. Boosters were reconnected at peak pressure.
†Balanced pressure section. Reservoirs disconnected at one end.

units being (lb. per sq. in.) per (inch cube) per (cu. in. of oil per hr.) for oil having a viscosity of 50 centipoises.

The process of solution for the radial pressure drop due to a rectangular load change is illustrated diagrammatically in Fig. 7. For general load variation the generalized form of the rectangular solution should be used. Some graphical integrations will be required in either case, and in making these it is best to divide the radius in equal elements $\Delta x$, and to use the average values of $x$ and functions of $x$ for each element in forming products, etc.

In part (1) of Fig. 7, the temperature distribution in the cable is shown for the selected instant of time. It is required for finding the oil viscosity, and is obtained from equation (**10**) or (**31**), using Chart 3.

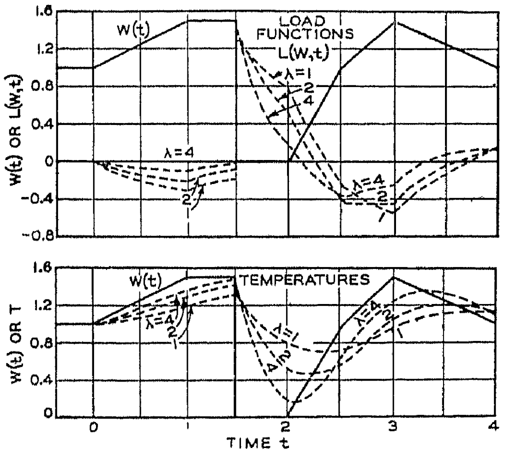


FIG. 6—GENERAL LOAD FUNCTIONS AND CORRESPONDING TEMPERATURES FOR TYPICAL LOAD CURVE

Part (2) shows the velocity of oil flow across the cylindrical surface at any point in the insulation, and for hollow core oil feed is obtained from equation (**20**) by replacing $r$ by $x$, and using Chart 4. For oil feed from a hollow core only, the contraction of the lead sheath will tend to supply the demand of some of the outer layers of insulation, and this should be taken into account. The oil supply due to the sheath is obtained from equation (**19**), using Chart 3. This is added, in the negative sense, to the integrated demand of the insulation. The demand due to the contraction of the conductor core in this case is not added, since it is not supplied by radial flow through the insulation, but by longitudinal flow in the core. However, for oil feed from the sheath only, $x$ would replace $R$ instead of $r$, in equation (**20**), and the oil demand $a_1$ equation (**18**) for the conductor would then be added in the positive sense to this summation, while the demand due to the sheath would not appear in the radial flow.

Part (3) shows the pressure drop across an element at any point in the insulation due to radial flow. It is the product of the velocity of oil flow (part 2) across the chosen element, and the resistance of the element to oil flow. Discontinuities in this curve are due to abrupt changes in paper density grading by zones, which introduce discontinuities in the insulation oil flow resistance factor, $\rho$. The viscosity factor, $\mu$, takes care of the variation of viscosity from element to element, due to the temperature distribution shown in part (1). The pressure drop is zero where the velocity is zero; in other words, where the supply due to the sheath has been exactly consumed by the demand due to the outer layers of insulation.

The total pressure drop due to radial flow is shown in part (4). It is the summation of the pressure drops across all the elements. This falls into two parts, since at some point in the insulation the pressure drop is zero. The pressure required at the core to supply the radial flow is the summation taken from the point of zero drop inwards to the conductor. The summation taken outwards from the zero point to the sheath is the pressure existing under the sheath due to its contraction. These pressures, part (4), must of course be altered by an additive constant for hydrostatic pressure so as to make the pressure at the inside (or outside) radius of the insulation equal to the pressure in the oil core (or sheath channels) at the moment under consideration. If the final resultant pressure is anywhere less than the partial pressure of solution of gases absorbed in the oil, then presumably voids will form. Influence of capillary attraction and electric stress on void formation, although important, are outside the scope of this paper.

When the insulation has oil feed from both core and sheath, then radial pressure drops are computed for expansion or shrinkage of the insulation only. Zero oil flow points in the insulation are assumed, by cut and try, to yield radial drops with a pressure difference equal to the difference of pressures actually existing between the two oil-feed sources.

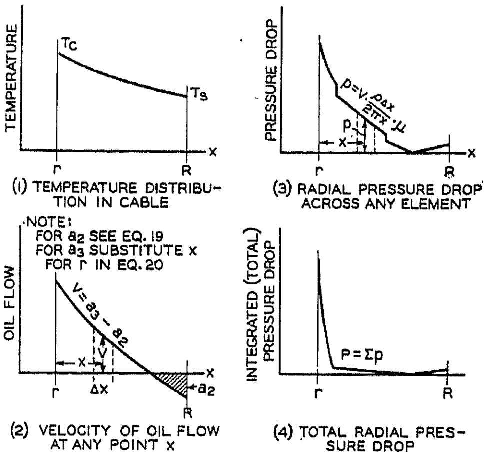
Following the procedure outlined, a graphical solution of the radial pressure drop was computed for the cable of line 7401. Under the most severe conditions of dropping load in the winter, the radial pressure drop was only a fraction of a pound per square inch, or much less than the minimum permissible oil pressure in the core. The radial distribution of the pressure drop is of interest. In spite of the higher temperature and smaller oil viscosity at the core, 50 per cent of the pressure drop occurs in the first 0.1 inch of insulation surrounding the conductor. This is because of the higher density of paper grading, smaller circumference, and concentrated oil flow near the conductor for hollow-conductor oil feed.

In the present design of most oil-filled cables the radial oil pressure drop is insignificant because of the small viscosity of the oil. However, in cables with "solid insulation" and thick compound this is not so, and the type of analysis given above, with obvious slight modifications, is useful in determining internal pressures and vacua developed during load variations.

## General Remarks

From a study of Appendix I it will be seen that the fundamental solution for the rectangular load change comes out in terms of Bessel functions (see equations (**5**), (**15**), (**16**), (**17**)). It will be seen also that it is necessary to evaluate the ratio of two constants ($A$ and $B$) and roots $u$ of a transcendental expression in Bessel functions, entailing a very great deal of complication and labor. In the simplified method given in the text, all necessity for any knowledge whatever of Bessel functions has been eliminated by Charts 1, 2, 3, and 4. Charts 1 and 2 also perform the operation of finding the roots of the transcendental expression. The saving in labor is so great that a novice using the simplified methods can work out the complete solution for temperatures and oil flows in a day, whereas without the aid of the charts it would require several days. In fact, the precise calculations of thermal and oil flow transients have been reduced to a form of such easy and prompt numerical application as to displace successfully less exact approximate methods on the criterion of ease and convenience alone.

The methods described in this paper were developed for problems of single-conductor cables. They can also be applied directly to three-conductor cables, using a per phase basis (*e. g.*, sheath thermal resistance = $3E$, etc.). For oil-filled three-conductor shielded cable with round conductors, the accuracy will be excellent. If the conductors are sector-shaped, good accuracy may be obtained by using the equivalent round conductors. For ordinary three-conductor cable with solid fillers and no shielding, the accuracy will be only fair.



(1) TEMPERATURE DISTRIBUTION IN CABLE

(3) RADIAL PRESSURE DROP ACROSS ANY ELEMENT

(2) VELOCITY OF OIL FLOW AT ANY POINT X

(4) TOTAL RADIAL PRESSURE DROP

Fig. 7—Solution for Radial Oil Pressure Drop in Cable Insulation

Illustration is for cable having oil feed from hollow core only

The assumption (**6**) that the thermal properties of a cable are constants is only approximately true. These properties do vary with temperature, but only slightly. Test data are inadequate, however, and the mode of variation is unknown, so that the assumption is a mathematical necessity. Some slight errors in results may be expected from this source.

Assumption (**5**) concerning dielectric loss permits the heat flow equations to be written for the dielectric loss very nearly as it actually exists in the cable. Other

TABLE IV—TABULAR METHOD OF EVALUATING $L(W, t)$

Example for load curve of Fig. 6, when $\lambda = 1$. Let $\Delta t = 0.5$

| (1) time, $t$ | | (2) $(W_t - W_o)$ | | (3) $e^{-\lambda t}$ | | (4) $\frac{(W_t - W_o)}{e^{-\lambda t}}$ | (5) $\sum_o^t (4)$ | (6) | (7) |
|---|---|---|---|---|---|---|---|---|---|
| $E$* | $A$* | $E$ | $A$ | $E$ | $A$ | | | $(\lambda\Delta t e^{-\lambda t})(5)$ | $L(W, t) = (6) - (2)$ |
| 0.00 | | 0.000 | | 1.000 | | 0.000 | 0.000 | 0.000 | 0.000 |
| | 0.25 | | 0.125 | | 0.779 | 0.161 | | | |
| 0.50 | | 0.250 | | 0.607 | | | 0.161 | 0.049 | −0.201 |
| | 0.75 | | 0.375 | | 0.472 | 0.795 | | | |
| 1.00 | | 0.500 | | 0.368 | | | 0.956 | 0.176 | −0.324 |
| | 1.25 | | 0.500 | | 0.286 | 1.745 | | | |
| 1.50 | | 0.500 | | 0.223 | | | 2.701 | 0.302 | −0.198 |
| | 1.75 | | −1.000 | | 0.175 | −5.71 | | | |
| 2.00 | | −1.000 | | 0.135 | | | −3.01 | −0.203 | +0.797 |
| etc. | | | | | | | | | etc. |

*$E$ and $A$ refer to values at end of increments and average values during increments, respectively.

investigators[2,3] have been content to assume, for the sake of simplicity, that the dielectric loss is concentrated at the conductor or sheath, or divided between them. The error due to this assumption is illustrated in Fig. 8.

Field tests indicate that the convenient assumption of constant duct temperature holds for the first one or two hours of the transient, but for longer times or very large change in total heat losses the changes in duct temperature must be taken into account. The accuracy with which cable transients can now be handled justifies the removal of this remaining major source of error in practical problems. This can best be done by study of field observations on conduit temperature transients under controlled conditions. The difference between theoretical and observed cable temperature or oil flow transients can now be used as a direct and convenient measure to determine the duct temperature transient.

Since, in general, longer periods of time are considered in the general loading case than in the rectangular case, any inaccuracies in thermal constants or changes in duct temperature may accumulate to appreciable error, the duct temperature transient being by far the most important. In such cases some empirical correction for duct temperature should be made.

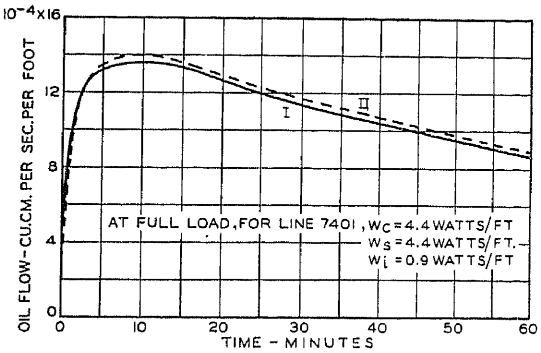


FIG. 8—OIL DEMAND OF TYPICAL CABLE (LINE 7401) DUE TO DROPPING FULL LOAD, AND VOLTAGE

I—Dielectric loss properly distributed in insulation
II—Dielectric loss assumed concentrated at conductor

## CONCLUSIONS

1. A reasonably simple solution has been obtained for cable transients due to a rectangular load change. The dielectric loss is distributed properly throughout the insulation. The theory has been verified by measurements on actual cables of the ordinary and oil-filled type.

2. Mathematical and graphical aids have been developed, which greatly reduce the time and labor required for numerical work. Solution and verification of a complete problem formerly required about a week. The same results can now be obtained in one day, with the aid of the new methods.

3. The transients due to load variations of any complexity whatever have been solved by using the well-known superposition theorem. The numerical work is very simple, and any desired degree of accuracy can be obtained.

4. A solution for the pressure distribution in the body of the insulation has been developed.

5. Some of the constants of cable insulation needed for use in thermal and oil-flow problems are relatively new. Many of the values now in use for these constants are based on only a few scattered observations. Further laboratory and field data should be obtained.

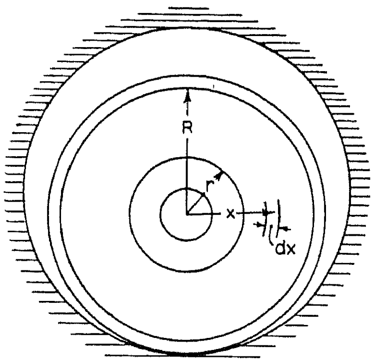


FIG. 9—CABLE IN DUCT

## ACKNOWLEDGMENT

The authors wish to acknowledge valuable suggestions regarding this paper, from Mr. Elwood Church of the Edison Electric Illuminating Company of Boston. They also desire to express appreciation to the Commonwealth Edison Company and to the Utilities Research Commission for assistance in its preparation.

## Appendix I

### SOLUTION FOR INSTANTANEOUS LOAD CHANGE

*Temperatures*

For any single-conductor cable such as shown in Fig. 9, the fundamental temperature equations in space and time for a change in losses of the type shown in Fig. 10 are:

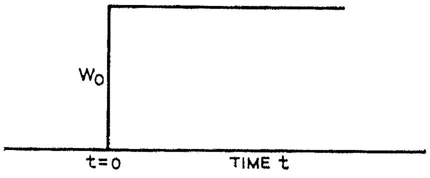


FIG. 10—RECTANGULAR LOAD CHANGE

$$-W = \frac{2\pi x}{p}\,\frac{\partial T}{\partial x} \tag{1}$$

$$\frac{\partial T}{\partial t} = \frac{2\pi x\,dx\left(\dfrac{KV}{x\log R/r}\right)^2 w - \dfrac{\partial W}{\partial x}\,dx}{2\pi x\,dx\,q} \tag{2}$$

Assuming the power factor of the dielectric is uniform,

$$W_i = \frac{2\pi (KV)^2 w}{\log R/r} \tag{3}$$

From equations (**1**), (**2**), and (**3**) we get:

$$pq \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{1}{x} \frac{\partial T}{\partial x} + \frac{p W_i}{2\pi x^2 \log R/r} \tag{4}$$

The complete solution of equation (**4**) is:

$$\begin{aligned} T = & \sum_{n=1}^{n=\infty} e^{-\frac{u_n^2}{pq} t} \left[ A_n J_o (u_n x) + B_n Y_o (u_n x) \right] \\ & + \frac{W_c''}{2\pi} p \log \frac{R}{x} \\ & + \frac{p(W_i'')}{4\pi \log R/r} \left( \log \frac{R}{x} \right) \left( \log \frac{Rx}{r^2} \right) \\ & + (W_c'' + W_i'' + W_s'') E + T_o \end{aligned} \tag{5}$$

where $J_o$ and $Y_o$ are Bessel functions of the first and second kinds respectively, both of order zero.

Applying the boundary conditions for $x = r$ and $x = R$, it can be shown[1] that:

$$\begin{aligned} B_n/A_n & = - \left[ \frac{M_1 - \phi\,(z\,.\,r/R)}{M_1 - \psi\,(z\,.\,r/R)} \right] \theta\,(z\,.\,r/R) \\ & = - \left[ \frac{(N/z^2 - M_2) - \phi\,(z)}{(N/z^2 - M_2) - \psi\,(z)} \right] \theta(z) \\ & = P\,(M_1, r/R, z) = Q\,(N, M_2, z) \end{aligned} \tag{6}$$

where

$$M_1 = \frac{Q_1}{2\pi q r^2},\ M_2 = \frac{Q_2}{2\pi q R^2},\ N = \frac{p}{2\pi E},\ z = Ru$$

and

$$\phi(y) = \frac{J_1(y)}{y J_o(y)},\ \psi(y) = \frac{Y_1(y)}{y Y_o(y)},\ \theta(y) = \frac{J_o(y)}{Y_o(y)} \tag{7}$$

The roots $u$ and the coefficient ratios $B/A$ for use in equation (**5**) are obtained from equation (**6**), preferably by graphical solution. The first three are generally sufficient. $A$ and $B$ are seen to be interdependent, and the ratio $B/A$ (the $P$ and $Q$ functions of equation (**6**)) will be found to vary from minus infinity to plus infinity. This is highly inconvenient in graphical work, and can be avoided by introducing the transformation:

$$K = (B/A)/(1 + |\,B/A\,|)$$

since the values of $K$ vary only from minus one to plus one.

It is useful to combine the $J$ and $Y$ Bessel functions, defining single new functions involving $K$ instead of $B/A$ as follows:

$$F_o(z, K) = (1 - |\,K\,|)\,J_o(z) + K Y_o(z) \tag{8}$$

$$F_1(z, K) = (1 - |\,K\,|)\,z J_1(z) + K z Y_1(z) \tag{9}$$

and to introduce the abbreviation:

$$\lambda_n = u_n^2/pq$$

Equation (**5**) may now be rewritten:

$$\begin{aligned} T = & \sum^{n} e^{-\lambda_n t} C_n F_o(u_n x, K_n) + \frac{W_c'' p}{2\pi} \log \frac{R}{x} \\ & + \frac{p W_i''}{4\pi \log R/r} \left( \log \frac{R}{x} \right) \left( \log \frac{Rx}{r^2} \right) \\ & + (W_c'' + W_i'' + W_s'') E + T_o \end{aligned} \tag{10}$$

where $C_n$ are the constants of integration, and must be selected to fit the limiting conditions in time.

The difference in temperature between the initial steady state ($t = o$) and the final steady state ($t = \infty$) is found from equation (**10**) to be:

$$T' - T'' = \sum^{n} C_n F_o(u_n x, K_n) \tag{11}$$

Equating (**11**) to the temperature difference obtained by consideration of only the initial and final steady states, the following relation is obtained:

$$\begin{aligned} \sum^{n} C_n F_o\,(u_n x, K_n) = & \left[ (W_c' - W_c'') \frac{p}{2\pi} \log \frac{R}{x} \right] \\ & + \left[ (W_i' - W_i'') \frac{p\,(\log R/x)\,(\log Rx/r^2)}{4\pi \log R/r} \right] \\ & + [(W_c' - W_c'') + (W_i' - W_i'') + (W_s' - W_s'')] E \end{aligned} \tag{12}$$

The numerical values of $C_n$ are obtained from equation (**12**). This is preferably done by evaluating all terms for as many different values of $x$ as there are roots required, and solving the resulting simultaneous equations in $C_n$. The first three values of $n$ are usually sufficient.

Equation (**10**) is now completely determined, and the temperature transients of the conductor and sheath may be obtained at once by making $x = r$ and $x = R$ in equation (**10**).

### *Oil Demands*

The three components of the total oil flow, due to variation in volume of the conductor, the sheath, and the insulation are readily seen to be:

$$a_1 = - Cc \frac{\partial T_c}{\partial t} \tag{15}$$

$$a_2 = - Vv \frac{\partial T_s}{\partial t} \tag{16}$$

$$a_3 = - \int_r^R \epsilon\,(2\pi x\, dx) \frac{\partial T}{\partial t} \tag{17}$$

The negative sign is introduced to make the flow positive (by definition) when the cable is cooling.

Performing the indicated operations on $T_c$, $T_s$, and $T$, the following expressions result, for unit change in loss:

$$a_1 = \frac{Cc}{pq} \Sigma u_n{}^2 e^{-\lambda_n t} C_n F_o(u_n r, K_n) = \Sigma f_{1n} e^{-\lambda_n t} \qquad (18)$$

$$a_2 = \frac{Vv}{pq} \Sigma u_n{}^2 e^{-\lambda_n t} C_n F_o(u_n R, K_n) = \Sigma f_{2n} e^{-\lambda_n t} \qquad (19)$$

$$a_3 = \frac{2\pi\epsilon}{pq} \Sigma e^{-\lambda_n t} C_n [F_1(u_n R, K_n) - F_1(u_n r, K_n)] = \Sigma f_{3n} e^{-\lambda_n t} \qquad (20)$$

For a unit change in copper loss only, the total oil demand would be $a_c = (a_1 - a_2 + a_3) = \Sigma f_{cn} e^{-\lambda_n t}$, and the same is true for changes in dielectric loss or sheath loss.

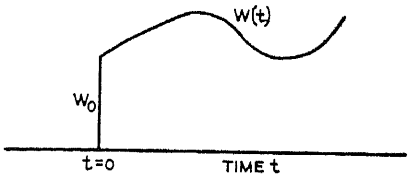


FIG. 11—FUNCTIONAL LOAD VARIATION

*General Expressions for Oil Demands and Temperature Transients*

Indicating copper, dielectric and sheath losses by subscripts $c$, $i$, and $s$, respectively, and letting subscript $n$ with $\overset{n}{\Sigma}$ refer to the summation with respect to successive time constants $\lambda_n$; the total oil demand due to an instantaneous change $\Delta W$ in any or all of the three losses can be written:

$$a = \overset{n}{\Sigma} [f_{cn} \Delta W_c e^{-\lambda_n t} + f_{in} \Delta W_i e^{-\lambda_n t} + f_{sn} \Delta W_s e^{-\lambda_n t}] \qquad (21)$$

In a similar manner the conductor and sheath temperatures can be written:

$$T_c = \overset{n}{\Sigma} [g_{cn} \Delta W_c e^{-\lambda_n t} + g_{in} \Delta W_i e^{-\lambda_n t} + g_{sn} \Delta W_s e^{-\lambda_n t}] + G(W_c'' + W_i''/2) + E(W_c'' + W_i'' + W_s'') + T_o \qquad (22)$$

$$T_s = \overset{n}{\Sigma} [h_{cn} \Delta W_c e^{-n\lambda t} + h_{in} \Delta W_i e^{-\lambda_n t} + h_{sn} \Delta W_s e^{-\lambda_n t}] + E(W_c'' + W_i'' + W_s'') + T_o \qquad (23)$$

In equations (**21**), (**22**) and (**23**) the coefficients $f$, $g$, and $h$ and the exponents $\lambda_n$ have already been determined.

## Appendix II

### SOLUTION FOR GENERAL LOAD VARIATION

Assume, first, that instead of the load remaining constant after the initial instantaneous change as shown in Fig. 10, it varies with time in any manner whatever, as indicated by $W(t)$ in Fig. 11. Duhamel's integral is applicable to this case. From equation (**21**), the "unit function" for oil flow, expressed for only one typical element, is:

$$a = f \Delta W e^{-\lambda t} \qquad (24)$$

where $f$ and $\Delta W$ are numerical constants.

Following Duhamel's integral, the general equation for oil flow due to load change of the type shown in Fig. 11 is readily found to be:

$$a = -f \left[ W(t) - \lambda e^{-\lambda t} \int_{v=o}^{v=t} e^{\lambda v} W(v)\, dv \right] \qquad (25)$$

where $v$ is a temporary integration variable which disappears when integration is performed and limits substituted. Since in this case $v$ is the only variable under the integral, any other variable may be substituted for $v$, say $t$.

For practical purposes, however, a solution for the type of load curve shown in Fig. 12 is more convenient than equation (**25**). The solution can obviously be obtained by subtracting from equation (**25**) the effect of the initial instantaneous change $W_o$. The resulting expression is:

$$a = -f \left[ \{ W(t) - W_o \} - \lambda e^{-\lambda t} \int_{v=o}^{v=t} e^{\lambda v} \{ W(v) - W_o \}\, dv \right] \qquad (26)$$

This entirely general solution is equally applicable to any element of oil flow or temperature change, provided the proper coefficients, $f$, $g$, or $h$ of equations (**21**), (**22**), and (**23**) are employed. For the sake of brevity, it is convenient to substitute $t$ for $v$ and to define the following "load function:"

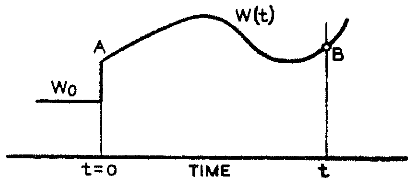


FIG. 12—GENERAL LOAD VARIATION

$$L_n = L_n(W, t) = \left[ \lambda_n e^{-\lambda_n t} \int_o^t \{ W(t) - W_o \} e^{+\lambda_n t}\, dt - \{ W(t) - W_o \} \right] \qquad (27)$$

Summing up for the space harmonics $n$ and restoring subscripts for the three sources of losses, the completely general expressions for temperatures and oil flow may be written at once. They are:

$$a = \overset{n}{\Sigma} [f_{cn} L_{cn} + f_{in} L_{in} + f_{sn} L_{sn}] \qquad (28)$$

$$T_c = \overset{n}{\Sigma} [g_{cn} L_{cn} + g_{in} L_{in} + g_{sn} L_{sn}] + G(W_c + W_i/2)_t + E(W_c + W_i + W_s)_t + T_o \qquad (29)$$

$$T_s = \overset{n}{\Sigma} [h_{cn} L_{cn} + h_{in} L_{in} + h_{sn} L_{sn}] + E(W_c + W_i + W_s)_t + T_o \qquad (30)$$

where subscript $t$ is substituted for functional notation $W(t)$.

The temperature at any point at any time for any general load variation is:

$$\begin{aligned} T_x = & \sum^{n} [C_{cn}F_o(u_nx, K_n)L_{cn} \\ & + C_{in}F_o(u_nx, K_n)L_{in} + C_{sn}F_o(u_nx, K_n)L_{sn}] \\ & + (W_c)_t \frac{p}{2\pi} \log \frac{R}{x} \\ & + (W_i)_t \frac{p}{4\pi \log R/r} \left( \log \frac{R}{x} \right) \left( \log \frac{Rx}{r^2} \right) \\ & + E\,(W_c + W_i + W_s)_t + T_o \end{aligned} \qquad (31)$$

## Appendix III

### Theory of Charts 1 and 2

The roots of equation (**5**) are obtained from equation (**6**), which for convenience was abbreviated to the form:

$$B/A = P(M_1, r/R, z) = Q\,(N, M_2, z)$$

The direct method of solution by plotting the $P$ and $Q$ functions and reading off intersections is most feasible, but considerable labor is involved. $P$ and $Q$ pass repeatedly from minus to plus infinity, which is very awkward in the graphical solution for intersections. However, very satisfactory results are obtained by plotting $y = \tan^{-1}(30/19)(P)$ and $y = \tan^{-1}(30/19)(Q)$ against $z$, which, from the nature of Bessel functions and the form of $P$ and $Q$, reduces the curves to a series of nearly straight slanting lines between ± 90° instead of $\pm \infty$. But for $y$ there is one and only one corresponding value of $B/A$, and the same is true of $K$. Therefore, the $y$ axis can be labeled in terms of $K$ instead of degrees, which gives directly the values required for obtaining the $F_o$ and $F_1$ functions.

The quantity $r/R$ appears in $P$ only as a multiplier of $z$. By plotting $P$ and $Q$ directly against $\log z$ as abscissas, any value of $r/R$ can be inserted in $P$ at will by a horizontal displacement of $P$ with respect to $Q$, of value $\log r/R$.

The $P$ and $Q$ functions have been calculated for a range of values of $M_1$, $M_2$, and $N$ sufficiently large to cover any reasonable design of cable. Instructions for use appear with the charts. The charts must be to the same scale.

## Appendix IV

### Routine Steps in Solutions for Transients

The most important operations in solving problems of cable transients are listed in sequence to serve as a guide in making actual computations. A few of the corresponding numerical values are given for line 7406. The figures should be of about the same order for any other cable, provided the design is not radically different. Some useful constants are given in Table I.

*1. Rectangular Load Change*

| Routine steps | Numerical values for line 7406 | | | | |
|---|---|---|---|---|---|
| 1—Calculate $M_1$, $M_2$, $N$, and $R/r$ | $M_1 = 0.645$, $M_2 = 0.078$<br>$N = 1\ 910$, $R/r = 2.007$ | | | | |
| 2—Find three roots from charts 1 and 2, obtaining $K_n$ and $Z_n$ | | $n = 1$ | $n = 2$ | $n = 3$ | |
| | $K_n =$ | −0.0476 | 0.2727 | −0.3254 | |
| | $Z = ru_n =$ | 0.738 | 2.214 | 4.493 | |
| 3—Find $F_o$ and $F_1$ functions from charts 3 and 4 | $F_o(ru_n,K_n) =$ | 0.833 | 0.299 | −0.108 | |
| | $F_1(ru_n,K_n) =$ | 0.312 | 0.952 | −0.135 | |
| 4—Calculate temperature at copper, mean insulation radius, and sheath for 1 watt loss | For 1 watt/cm. copper loss<br>$(T_c - T_o) = 106.8$; $(T_m - T_o) = 71.0$<br>$(T_s - T_o) = 45.8$ | | | | |
| 5—Set up and solve three simultaneous equations for $C_n$ | (1) $0.833C_1 + 0.299C_2 - 0.108C_3 = 106.8$<br>(2) $0.670C_1 - 0.159C_2 + 0.220C_3 = 71.0$<br>(3) $0.467C_1 - 0.327C_2 - 0.185C_3 = 45.8$<br>$C_1 = 116.2$; $C_2 = 30.66$; $C_3 = -7.94$ | | | | |
| 6—Multiply out the coefficients in the final equations | In Eq. (**10**) for $T_c$ (copper loss only): | $n = 1$ | $n = 2$ | $n = 3$ | Check |
| | $C_nF_o(u_nr,K_n)$ | 96.89 | 9.17 | 0.86 | 106.9 |
| | $u_n^2/pq$ | $1.34\times10^{-4}$ | $12.08\times10^{-4}$ | $49.60\times10^{-4}$ | |
| 7—Set up final equations, and solve for various values of $t$ | Copper temperature transient due to change of 1 watt copper loss per cm ($t$ in minutes)<br>$T_c = 96.89e^{-0.00804t} + 9.17e^{-0.0725t} + 0.86e^{-0.298t}$ | | | | |

*2. General Loading*

1—Obtain unit coefficients, using rectangular solution; for example, for line 7406 it was found that $g_{c1} = 96.89$, and $\lambda_1 = 0.00804$.

2—Arrange load curve in terms of copper, dielectric, and sheath loss.

3—Proceed according to Table IV, which is for $\lambda = 1$, and the hypothetical load curve of Fig. 6.

4—Multiply $L(W, t)$ by coefficients $f_n$ to obtain oil flow, and coefficients $g_n$ or $h_n$ for temperatures at copper and sheath.

## List of Symbols

$t$ = time in seconds
$r$ = inside radius of insulation
$R$ = outside radius of insulation
$x$ = radius of cylindrical element considered
$Q_1$ = total thermal capacity of copper conductor and free oil in strands and core (if any) per unit length, Joules per deg. cent.
$Q_2$ = total thermal capacity of sheath, armor, shielding tapes and free oil in channel or sheath flutes (if any) per unit length
$q$ = specific thermal capacity of insulation, per unit volume
$p$ = specific thermal resistance of insulation, per unit volume
$w$ = dielectric loss per unit volume at unit voltage gradient
$E$ = thermal resistance, sheath to duct, per unit length
$G$ = thermal resistance, copper to sheath, per unit length
$T$ = temperature deg. cent. at point and time considered
$T_o$ = duct temperature
$W$ = watts heat flow across cylindrical element at $x$
$W_c$ = watts copper loss
$W_i$ = watts dielectric loss per unit length of cable
$W_s$ = watts sheath loss
$C$ = total volume copper conductor and free oil per unit length
$V$ = total volume inside of lead sheath or inside of shielding tape, if any

$c$ = effective volumetric thermal coefficient of expansion of copper core and free oil combined, per deg. cent.
$\epsilon$ = effective volumetric thermal coefficient of expansion of insulation, oil and paper combined, per deg. cent.
$v$ = effective volumetric thermal coefficient of expansion of lead sheath, corrected for free oil in channel or sheath flutes, if any
$a_1$ = rate of oil flow contributed by conductor and core, cu. cm. per sec. per unit length
$a_2$ = rate of oil flow contributed by lead sheath shrinkage or expansion, corrected for oil in flutes or channels, if any
$a_3$ = rate of oil flow contributed by insulation
$a$ = total resultant rate of oil flow, per unit length
$\rho$ = resistivity of insulation to radial flow of oil of standard viscosity
$\mu$ = correction applied to $\rho$ to take account of actual viscosity of oil
$\Delta$ = finite increment of quantity considered

NOTE: Thermal "constants" are assumed independent of temperature.

Subscripts $c$, $i$, and $s$ refer to conductor, insulation, and sheath, respectively.

Superscript (′) indicates conditions before transient.

Superscript (″) indicates conditions during and after transient.

All logarithms are to base $e$.

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5. *Oil-Filled Cable and Accessories*, by R. W. Atkinson and D. M. Simmons, A.I.E.E. TRANS., Vol. 50, No. 4, December 1931, p. 1421.
6. *Temperatures in Electric Power Cables under Variable Loading*, by Elwood Church, A.I.E.E. TRANS., Vol. 50, No. 3, September 1931, p. 982.
7. "Thermal Properties of Underground Cables," *N.E.L.A. Publications* No. 267-91, August 1927, p. 5.

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## Discussion

**E. A. Church:** A significant fact to be noted in this paper is the reduction of relatively difficult mathematics to simple arithmetic by the expedient of combining Bessel functions in charts enabling the coefficients and exponents in the temperature and oil demand equations to be evaluated in a minimum of time.

The method used by the authors enables discontinuities in the load curve to be taken into account with greater accuracy than some methods previously employed for computing temperatures under variable loading, a factor of extreme importance in computing stresses in oil filled cables, since the stress or void formations depend as much upon the rate of change of temperature as upon the temperature change itself. Sudden discontinuities on the load curve will create the greatest rates of change of temperature.

Another important fact which it is well to emphasize is that the temperature and oil demand equations for suddenly applied load (unit function in Heaviside terminology) *are functions of the constants of the cable only*. Thus only one computation of coefficients need ever be made for any given size and type of cable. These may be used for the solution of any load variation whatsoever, by an application of the Duhamel integral.

The Duhamel integral is applicable to any physical problem where the principal of superposition is valid. In the general case it is expressed as follows in a solution for temperature:

$$T(t) = Q(t)\,A(o) + \int_0^t \frac{\partial}{\partial t} A(t - \lambda)\, Q(\lambda)\, d\lambda.$$

where the terminology of the paper is used. $A(t)$ is the solution for the unit function and $A(o)$ its value at the initial instant: $\lambda$ is a variable time parameter under the integral sign which makes it difficult to evaluate in the general case. Where $A(t)$ can be expressed in the form of a series of exponential terms the integral takes the form shown in the paper and can be solved as an ordinary definite integral.

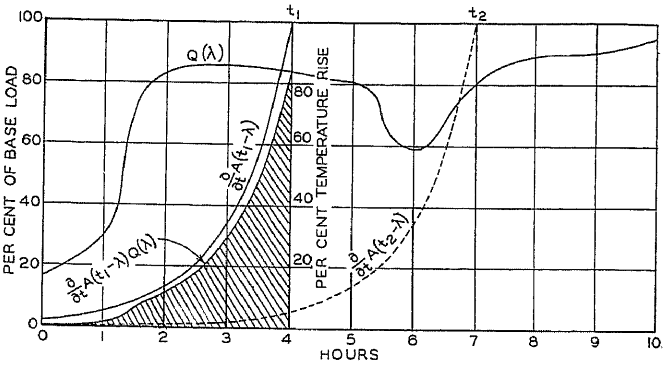

FIG. 1—ILLUSTRATION SHOWING METHOD OF INTEGRATING

$$\int_o^t \frac{\partial}{\partial t} A\,(t - \lambda)\; Q\,(\lambda)\; d\lambda$$

The shaded area represents:

$$\int_0^{t_1} \frac{\partial}{\partial t} A\,(t_1 - \lambda)\; Q\,(\lambda)\; d\lambda$$

Hence, if the solution for a suddenly applied load can be obtained by test, the solution for any general load variation may be easily calculated from it, provided the test curve can be represented by a simple mathematical formula such as a series of exponentials. Theoretically it is quite possible to represent a curve of the type obtained in this problem by such a series, but the practical difficulties encountered in solving for the coefficients and exponents of each term of the series, even though only a few terms are used, make it easier to evaluate the integral graphically. This may be done as follows:

Plot the value of $\frac{\partial}{\partial t} A(t)$ on transparent paper to the same scale as a plot of the loading curve. Superimpose this plot of $\frac{\partial}{\partial t} A(t)$ reversed on the time axis, and with its origin shifted to the right of the origin of the loading curve an amount representing time $t_1$, as shown in the accompanying illustration. It then corresponds, on the scale of the loading curve, to $\frac{\partial}{\partial t} A(t - \lambda)$. Plot the product of $\frac{\partial}{\partial t} A(t - \lambda)$ and $Q(\lambda)$ and integrate this product curve from $o$ to $t$. Repeat this process from time $t_2$, and so on for all the values of time at which it is desired to compute the temperature.

It must be remembered that for every new value of $t$ chosen a separate product curve will be necessary, and is obtained by shifting the axis of the graph of $\frac{\partial}{\partial t} A(t - \lambda)$ to the new value of $t$. The plot of these various definite integrals will be the evaluation of $\int_0^t \frac{\partial}{\partial t} A(t - \lambda)\, Q(\lambda)\, d\lambda$. It is then a simple matter to add the other term of the Duhamel integral to obtain the complete temperature variation with respect to time. This graphical scheme of integration can be carried out very easily by means of a planimeter for obtaining the area under the product curve.

If a planimeter is available it may profitably be used in evaluating the coefficient, $L_n(W,t)$ in equations (27) and (31) of the paper rather than the step-by-step method described.

**F. H. Buller:** Those who have occasion to make temperature transient or oil demand calculations on cables are very much indebted to Messrs. Miller and Wollaston for the simplifications which they have devised to render computations less laborious.

The large scale editions of charts 1 and 2 have been found very useful in obtaining approximate values of the roots of equation (6). While the charts give values which are close enough for all but the most accurate work for the first root of the equation, we have found it advisable to check the values obtained from the charts by substituting in equation (6) and plotting in the usual way where greater accuracy is required, especially in the case of the roots of the higher order than the first. However, in most cases it is found that the charts give values which are close enough for approximate work; and even when more exact results are necessary the charts are very useful in reducing the amount of labor involved in the solution of equation (6) to an absolute minimum. We believe that the limitations of the charts lie in the mechanics of reproduction rather than in the underlying theory. As the authors point out, it should be theoretically possible to construct charts which would give any desired degree of accuracy from the equations presented in the paper.

The value of charts 3 and 4 in simplifying numerical calculations is so obvious as to require no comment.

The application of the principle of superposition to thermal calculations is, of course, not new; and the Duhamel integral has long been a familiar function. However, Messrs. Miller and Wollaston have given a very thoroughgoing treatment showing exactly how these aids to analysis can be applied to this particular problem and we feel that this treatment will be of such assistance to those who have to deal with this subject as to constitute a distinct advance in the art of thermal transient calculations.

The method of evaluating the coefficient $C_n$ described by the authors, is simple in theory and usually useful in practise, particularly if only three terms of the infinite series for temperature and oil demand are required. As the number of terms increases, it is found that the amount of numerical work involved in this method increases much more rapidly; and the method soon becomes rather unmanageable because of this. Under such conditions it is better to use the mathematical solution presented in the A.I.E.E. TRANS., December, 1931, pages 1411 to 1420, and the *G. E. Review*, September, 1931, by Mr. G. B. Shanklin and the present discussor. This solution has been extended to cover the case of dielectric loss, distributed in the usual manner; the complete equations, covering the case where copper loss, sheath loss, and dielectric loss exist simultaneously, are given below.

In equation (2) $W_c$ is the copper loss, $W_s$ the sheath loss, and $W_d$ the dielectric loss, in watts per foot of cable. The definitions of the other quantities are given in the appendix to the aforementioned paper. (TRANS. A.I.E.E., Dec. 1931, page 1420.)

The first term in the square parenthesis in the numerator of equation (2) gives the effect of the copper loss; the second term, that of the sheath loss, and the last term, which contains the two integrals, gives the effect of the dielectric loss.

On examining the authors' Fig. 8, it would appear that the error in maximum oil demand introduced by assuming the dielectric loss concentrated on the copper, is not very serious at 132 kv, being of the order of 3 per cent and on the safe side. A more accurate result would probably have been obtained if the dielectric loss had been assumed to be equally divided between the conductor and the sheath. A still more accurate result could be obtained by using equation (1) above. The additional complication involved in the use of this equation might be warranted at 230 kv.

The statement is made that, "A small discrepancy between measured and calculated values for the initial part of the oil demand curve is not conclusive evidence of void formation in an oil filled cable as some have maintained." This statement, of course, is correct as it stands, but is nevertheless somewhat misleading. It has never been contended that *any* small discrepancy may be accounted for by void formation. As the authors point out, the discrepancies between the measured and calculated curves may also be due to the following factors:

(a) Errors in the method of calculation, for example

1. The use of approximations such as the graphical evaluation of $C_n$ in the manner described by the authors.

2. The omission of terms in the infinite series, which may be important in the first part of the transient.

(b) Numerical errors in calculations.

(c) Errors in measurement.

(d) Errors due to the use of inaccurate values for the constants of the cable.

(e) Errors due to variations in the "constants" of the cables with temperature, etc.

COMPLETE EQUATIONS FOR TEMPERATURE TRANSIENTS ON CABLES

$$T = \sum A_n \left[J_o(u_n x) - K_n Y_o(u_n x)\right] \epsilon^{-u_n^2 t/p'q} \tag{1}$$

$$p_{in} = \frac{\dfrac{p'\Delta_1\Delta_2}{\pi}\left[\dfrac{W_c\Delta_1}{u_n r} - W_s\Delta_2 + \dfrac{W_d\,\Delta_1\,\Delta_2}{\log R/r}\left\{\displaystyle\int_r^R \frac{J_o(u_n x)dx}{x} - K_n \int_r^R \frac{Y_o(u_n x)dx}{x}\right\}\right]}{\left[\left\{M_2(u_n R)^2 - N\right\}^2 + (1 + 2M_2)(u_n R)^2\right]\Delta_2^2 + \left[2M_1 - 1 - M_1^2(u_n r)^2\right]\Delta_1^2} \tag{2}$$

The integrals in the numerator have been evaluated in series form, as follows

$$\int \frac{J_o(x)}{x}\,dx = \log x + \sum \frac{(-1)^n (x/2)^{2n}}{2n \cdot n!^2} \tag{3}$$

$$\int \frac{Y_o(x)}{x}\,dx = \frac{\log^2 x}{2} - \sum \frac{(-1)^n (x/2)^{2n}}{2n \cdot n!^2}\left(1 + \frac{1}{2} + \frac{1}{3} + \ldots + \frac{1}{n} + \frac{1}{2n} - \log x\right) \tag{4}$$

The errors under heading (a) may in general be reduced to a negligible value by the use of the exact mathematical solution and by the use of as many terms of the series as may be needed for the accuracy required. It should be noted that the evaluation of $C_n$ by the method proposed by the authors becomes more and more precise as terms are added to the series.

The numerical errors may be almost entirely eliminated by careful checking. If the value of $C_n$ is calculated mathematically and the temperature as calculated from equation (1), above, is compared with the known limiting condition at time $t = 0$, a valuable check on the numerical work is obtained. This check is impractical if the method of calculation of $C_n$ advocated by the authors is used.

With regard to errors in measurement, we appreciate that the authors were working under great difficulties when they tried to obtain reliable field tests on oil demand. Laboratory tests are much easier to control and more accurate data may be expected from such tests. The agreement between test and calculated values as given by the authors in Table II, is very good for a field test. Laboratory tests, however, would probably show even closer agreement.

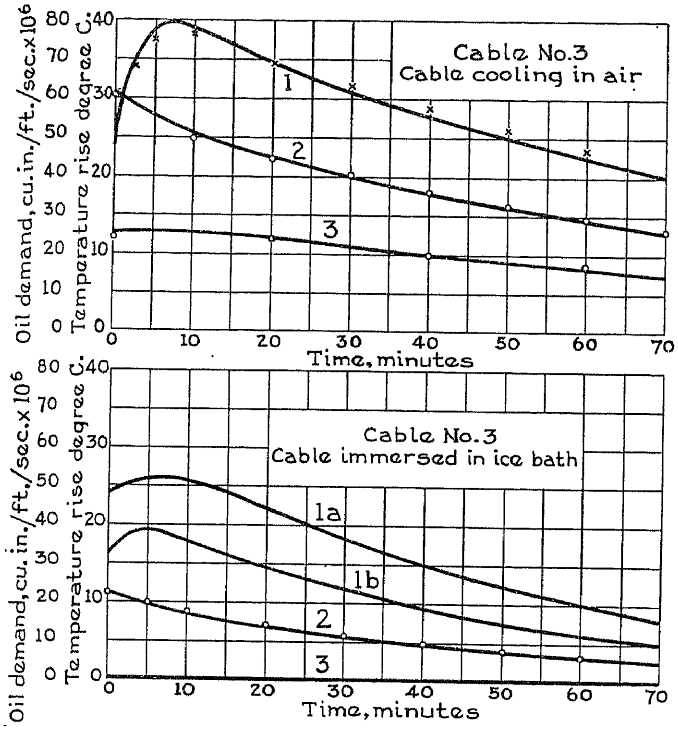

Fig. 2—Oil Demand and Supply After Dropping Load. Theoretical Calculations Shown by Full Line Curves. Test Results Shown by Plotted Points and by Curve 1*b* in Ice Bath Test

1 —Oil demand and supply
1*a*—Calculated demand
1*b*—Measured supply
2 —Copper rise
3 —Sheath rise

The source of errors which is at present the most difficult to eliminate is given under headings (d) and (e). Care is taken in laboratory work to use the constants which apply to the actual cable under test, as far as possible. It is more difficult to determine these constants in the field. Agreement between laboratory tests and calculated values of temperature indicates that the variation of the cable constants with temperature produces comparatively little effect on the transient, excepting in the case of copper resistance. This is well brought out by the authors in their Fig. 1, and by Fig. 2 of this discussion.

In short, if an attempt is made to estimate void formation by comparing a calculation based on assumed constants with a field test, the results would probably not be very accurate. Moreover, it has been brought out that when such an attempt is made it is advisable to use the exact mathematical solution rather than the more approximate graphical solution. It does not necessarily follow, however, that measurements made in the laboratory under properly controlled conditions will not give more satisfactory results.

Fig. 2 in the above-mentioned paper by G. B. Shanklin and F. H. Buller, A.I.E.E. Trans., December 1931, page 1414, shows what can be done in the way of obtaining an exact check between calculated and test values in the laboratory. While the agreement of calculation with test is not perfect in the case of the oil demand curve for cable No. 2, it is on the whole very good. In this case we would certainly hesitate to say that the discrepancies are due to void formation. It should be noted that both cables 1 and 2 were impregnated with a light oil, carefully degasified.

Fig. 2 of this discussion shows two tests on cable 3, which was treated with a heavy oil. A cooling test in air gives a reasonably good check with calculations, indicating that the constants of the cable were known with a good degree of accuracy and did not change materially during the test.

When the same cable is immersed in an ice bath, its temperature is materially reduced and the viscosity of the compound very much increased. The high viscosity of the compound should tend to give rise to void formation. Although there are apparent signs of void formation, there is some question as to whether a discrepancy between tests and calculation is or is not entirely due to void formation in the case where the cable was cooled in air. In our opinion, there is no question but that the discrepancy was due to void formation in the case where the cable was immersed in the ice bath. The agreement between the calculated and measured temperature rises practically excludes the possibility of errors in calculation or of variation of any of the cable constants, with the possible exception of the coefficient of expansion of the compound with temperature. Tests made on this compound indicate that the change in coefficient of expansion over the range considered is not sufficiently large to account for the observed discrepancy. Void formation is the only hypothesis left.

It should be noted that the cable length in this test was short, and was provided with a hollow core. A line in service would have much more serious void formation due to longitudinal pressure drop. Even if a hollow core were used with this type of compound, serious void formation might be expected in service due to longitudinal drop.

Of course, as stated above, the hypothesis of void formation cannot be used to account for any and all discrepancies between observation and calculation. A careful check of both test and calculation and a certain amount of judgment are needed before this hypothesis should even be advanced in any particular case; and in no case should the discrepancy be taken as more than an approximate measure of the amount of void formation likely to occur in a given cable.

However, it is believed that a pronounced discrepancy between calculation and test will almost certainly indicate the existence of void formation under certain conditions.

**Robert J. Wiseman:** The paper by Messrs. Miller and Wollaston is an abstract of a more comprehensive treatise on the subject of thermal transients and pressure gradients in cables. In the past, we have had to consider the design of a cable based on the dielectric strength and dielectric power factor of the insulation. With the improvement in oil and paper as well as manufacturing methods, we have reached a high degree of perfection, but we find now that it is necessary for us to consider more seriously the temperature gradients and the resulting pressure gradients as a cable goes through its loading cycle. This involves the thermal and physical properties of the insulation, hitherto not considered as of great importance, except as limiting the current carrying capacity.

The application of the analysis to both solid and oil-filled, single and multiple conductor cables is most valuable. Researches being carried out by some of the cable manufacturers show internal pressures in solid cable much higher than realized. We have found very high pressures at the conductor and sheath with no indication of a positive pressure in the middle of the insulation. We did not appreciate why this was so. It is very likely that it can be explained by analyzing mathematically along the lines in this paper what should take place. We are now making such a study. It is possible by studying how a cable acts thermally to decide what the physical characteristics of the oil should be in order to prevent excessive internal pressures and, therefore, eliminate the expansion of the lead sheath with its attendant shortcomings.

**K. W. Miller and F. O. Wollaston**: It is a source of considerable satisfaction to us to receive the favorable comment of Messrs. Church, Buller and Wiseman, as well as to know, from private correspondence with individuals who did not discuss our paper, that the methods and charts described by us are proving of practical use to computers, designers, and users of underground cables.

Mr. Church has described a graphical method of obtaining the generalized $L$ function for load curves of any kind whatever and has also suggested the use of a planimeter for this purpose. It may be mentioned here that a very simple mechanical device may be constructed for this purpose from a watthour meter disk and damping magnets, one spring and two pointer arms. When one pointer is made to trace the load curve (plotted in terms of watts loss *vs.* time), then the second arm will automatically draw (to the same scale) the $L_n$ function curve for any selected numerical value of the exponent $\lambda_n$.

Mr. Buller has discussed the convenience and accuracy of the numerical results to be expected from use of our charts and our method of obtaining coefficients $C_n$. An inspection of Charts 1 and 2 indicates that the roots $Z_n$ and hence exponentials $\lambda_n$ will always be very accurately determinable. The first $K_n$ ratio can also be very accurately determined but, for larger roots, $K_n$ decreases in accuracy owing to the points of intersection between curves becoming less definite. However, our simultaneous equation method of solution for coefficients $C_n$ automatically compensates for small inaccuracies in $K_n$ for the curve of initial condition (when $t = O$) and, from the nature of exponentials, the terms involving the largest roots (and $K$ values of greater uncertainty) are the first to shrink to insignificance with increasing time. Briefly stated, mathematically it may be said that the charts for $K_n$ and $Z_n$ and equations for $C_n$ automatically guarantee an accuracy in direct ratio to the importance of the term involved with respect to both space and time.

On physical grounds it may be noted that a small percentage of uncertainty in the thermal constants or cable dimensions will introduce appreciable uncertainty into the $K_n$ values, increasingly so with larger roots, because of the lesser definiteness of the points where the $P$, $Q$ curves intersect, for larger values of $Z_n$, no matter how carefully they may be plotted or computed by formulas. Conversely, for larger roots, increasing changes in $K$ are required for equal physical significance. Intuition or judgment correctly tells one that small changes in the basic (physical) constants cannot have a large effect on the final result and hence these apparently sensitive changes in $K_n$ for large roots are not serious. Therefore, our charts and methods, as well as Mr. Buller's formulas, give substantially the same results as experiments. In view of the fact that the thermal constants of a problem will rarely be known to a certainty beyond the 0 to ±3 per cent accuracy obtainable with our charts, we feel that our methods are sufficiently accurate. For the same reasons, we feel that our method of handling dielectric loss is fully as accurate as the data justify, and very convenient. After all, this is a problem in engineering, not in precision astronomy.

Mr. Buller also raises the question of checking of numerical results. Assuming $M_1$, $M_2$, $N$ and $R/r$ have been correctly determined, this falls naturally into two parts: errors in determining (1) root-ratios $Z_n$, $K_n$, and (2) coefficients $C_n$. In our solution no simple method is available to check the first, but with a little practise one must be very careless to misuse Charts 1 and 2 and checking by repetition is a matter of only a few minutes. For the second part, contrary to Mr. Buller's statement, the $C_n$ values can easily be checked against the curve of initial fit by simple addition. (See Appendix IV, step 6, compared to step 5.) With Mr. Buller's equations, errors will not be discoverable until nearly all the hard work has been completed and the $C_n$ values are obtained and checked against the curve of initial fit. If discrepancies occur, there is in general no way to know where the error was made and one or more mistakes may be very laborious to find and correct when working with such complicated formulas.

With respect to void formation, we do not maintain that differences between computed and experimental curves might not be due in part to void formation, but that, taken alone, this is not a necessary conclusion and that our radial pressure drop calculation enables a more valid conclusion to be reached. We compute the possibility directly rather than as a small difference between two large, somewhat uncertain, values. In this, Mr. Buller apparently agrees, although some statements in previous articles on this point are misleading.

We are pleased to know that Doctor Wiseman is applying the theory outlined to studies of the behavior of compound in cables of the solid insulation type. We have tried to emphasize that the utility of our methods is not limited to cables of the oil-filled type but, on the contrary, a practical analytical method is now available enabling engineers to attack successfully some of the problems of void formation and migration and pressures of compound in solid type cables.

# Voltage Regulation of Cables Used for Low-Voltage A-C. Distribution

BY H. R. SEARING*
Fellow, A.I.E.E.
and
E. R. THOMAS†
Member, A.I.E.E.

IT is generally recognized that the design of a distribution system for alternating current at low voltages does not depend primarily upon the selection of a conductor size which shall be thermally sufficient to carry the load, but depends upon the voltage regulation limits which will be satisfactory for lighting especially when combined light and power loads are carried on the same circuit.

The increment starting currents of induction motors are not only large compared to the running current but are of low power factor as well. In order to avoid flicker in illumination where light and power loads are combined, it is necessary to keep the circuit reactance to a consistent minimum in order to minimize the effect of increment motor starting currents of low power factor.

Improved voltage regulation of power circuits will also result in economies due to the relations which exist between voltage and torque in the induction motor. This is particularly true where torque is the application limitation as with elevators and printing machinery.

Voltage regulation by definition is the ratio of the difference between the impressed voltage and received voltage to the received voltage expressed as a percentage and thus for any circuit carrying alternating current it becomes a function of the magnitude of the current, the power factor, and the circuit impedance. Only the first of these factors approximates a simple linear relation to the voltage regulation.

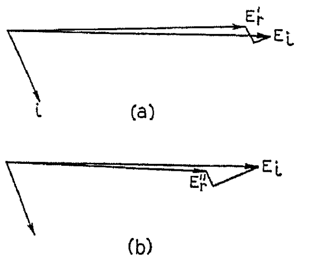

Fig. 1—Comparative Vector Diagrams

Showing resulting voltage drops with low and high reactance circuits at a low power factor load

Circuits which contain the larger values of inductance give poorer voltage regulation with low power factor currents because the inductive voltage drop is more nearly in phase with the line voltage. This may be readily noted in the comparative vector diagrams shown in Fig. 1 where (*a*) shows the resulting voltage regulation obtained with a circuit having a small value of reactance and (*b*) that obtained with a circuit having approximately three times the reactance of the former circuit.

The current carrying capacity of a conductor is usually thought of in terms of its physical size but this physical size is an index to only one of the components of its impedance and thus in itself does not furnish any simple picture of what may be expected in voltage regulation in the general case.

If consideration were given only to regulation at unity power factor, then the physical size of the conductor would furnish an index of the inverse proportionality between voltage regulation per unit length and increasing sizes of conductors. However, if load currents of lower and lower lagging power factors are applied it soon becomes apparent that the inductance component of the impedance becomes the major parameter affecting the voltage regulation.

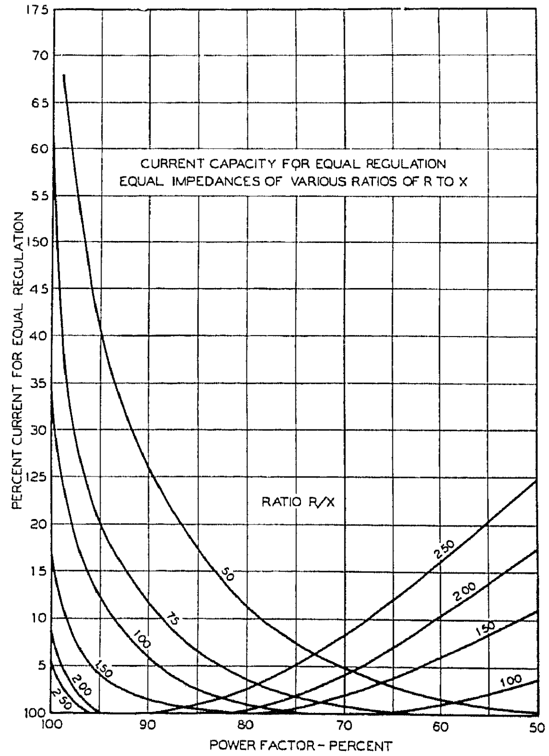

Fig. 2—Ratio of Load Current at Various Power Factors to Minimum Current

To give equal values of voltage regulation with equal circuit impedances for various ratios of *R* to *X*

If a choice of circuits constants be made, such that certain ratios of resistance to reactance obtain, it is possible to produce quite different trend curves of

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*The New York Edison Co. and The United Electric Light & Power Company.

†The United Electric Light & Power Co.

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voltage regulation. Considering a constant value of voltage regulation for circuits having equal values of impedance, the ratio of current at any power factor to the minimum current giving that value of regulation may be calculated for various ratios of resistance to reactance. (See Appendix I.) Such a set of data is shown graphically in Fig. 2.

It will be noted that if the ratio of resistance to reactance is less than unity the per cent current which may be carried to give equal values of regulation decreases very rapidly with decreasing power factor. On the other hand, if a relatively large ratio of resistance to reactance is selected, the current becomes an increasing function for equal regulation at the lower power factors. Thus, if a choice could readily be made, it would seem desirable to choose a ratio of resistance to reactance of something between 1.5 and 2.0 for a circuit which would be subject to variable lagging power factor loadings as ratios near these values tend to give more nearly uniform voltage regulation over a range of power factors from 50 to 100 per cent. In applying such a selection of ratios of resistance to reactance to the design of alternating current circuit, one is immediately faced with the problem that while the resistance per unit length of the circuit is variable depending only on the physical size of the conductor, the reactance per unit length of the given circuit is almost independent of the physical size of the conductors and for a single circuit with cables can only be changed by changes in cable construction. Thus in order to obtain a certain optimum ratio of resistance to reactance for a circuit, there are in general, three courses of attack; first, for a given physical size, the reactance component may be changed by changing the cable construction (single conductor or multi-conductor cables with sector type or concentric type construction), second, by changes in the physical size of the conductor, and third, by paralleling two or more circuits.

### CONCENTRIC CABLES

Concentric cable construction has long been used for feeders on low-tension d-c. distribution because of the space factor consideration. For three-phase a-c. distribution this type of construction applied to three conductors instead of two gives the minimum reactance per unit length which it is possible to obtain with a single circuit for a fixed value of insulation thickness. In addition, this construction gives a very flat regulation curve for physical conductor sizes which would be commonly used for distribution purposes, that is, sizes from No. 4/0 to 500,000-cir. mils. The construction, however, does not lend itself readily to permit splicing operations to be made while the cable is alive, therefore, while this type of construction might prove very satisfactory for radial feeders to individual motors, it would not be practical for use in making up a secondary network grid.

### SECTOR CABLE, THREE-CONDUCTOR

Three-conductor sector cable provides, by constructional features, the next higher reactance per unit length for single circuits. Its use again is subject to the same limitations as for the concentric type construction in that splicing operations cannot be made readily while the cable is alive.

### SINGLE-CONDUCTOR CABLE

Single-conductor cables have the highest reactance per unit of length of all the types of cable construction in commercial use due to the increased spacings which result between conductors. While the disadvantage of the relatively high reactance component has long been realized this type has found almost universal favor in the construction of alternating current mains because of practical splicing considerations. If it were desired to obtain a relatively flat regulation curve with a single circuit of single-conductor cable, it would be necessary to use rather small physical sizes in order that the optimum ratio of resistance to reactance be maintained.

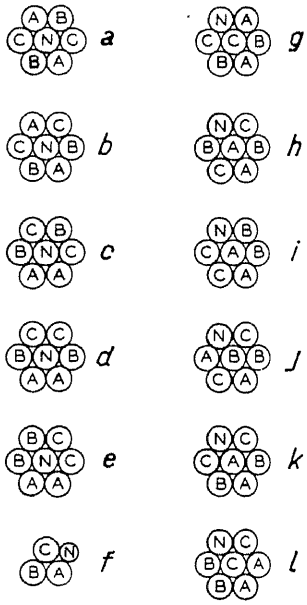

FIG. 3—PHASE CONDUCTOR POSITIONS FOR VARIOUS TWIN CIRCUIT ARRANGEMENTS

### MULTI-CIRCUITS OF SINGLE-CONDUCTOR CABLES

Since information on single-conductor cable indicates that good regulation would obtain over a considerable range of power factor only with the use of small physical sizes, it would of course become obvious that several circuits of the smaller size cables could be paralleled thereby maintaining the same ratio of resistance to reactance while obtaining the actual values of resistance to provide sufficient current carrying capacity. However, when two or more circuits are placed in close proximity the reactance of the parallel circuit is made up not only of the self-inductance of the circuit but also of the mutual inductance between the circuits. By altering the physical arrangements of conductors in a twin circuit for three-phase distribution made up of six conductors it is possible to have the mutual inductance become either additive or subtractive from the self-inductance of each circuit. This results in the overall reactance of the circuit being either somewhat greater or somewhat less than one-half the reactance of a single circuit. Formulas are given in the appendix for calculating the various arrangements.

The voltage regulation which obtains with twin circuits depends in part also on the mutual phase relations which exist between the several conductors. These various arrangements are shown in Fig. 3. The arrangement (*a*) results in the minimum voltage regulation and arrangement (*e*) in the maximum voltage regulation. A comparison of the voltage regulation which obtains with these two limiting arrangements of twin circuits of No. 4/0 single-conductor cables and with a single circuit of 500,000-cir. mil single-conductor cable carrying the same load current, 400 amperes, is shown in Fig. 4.

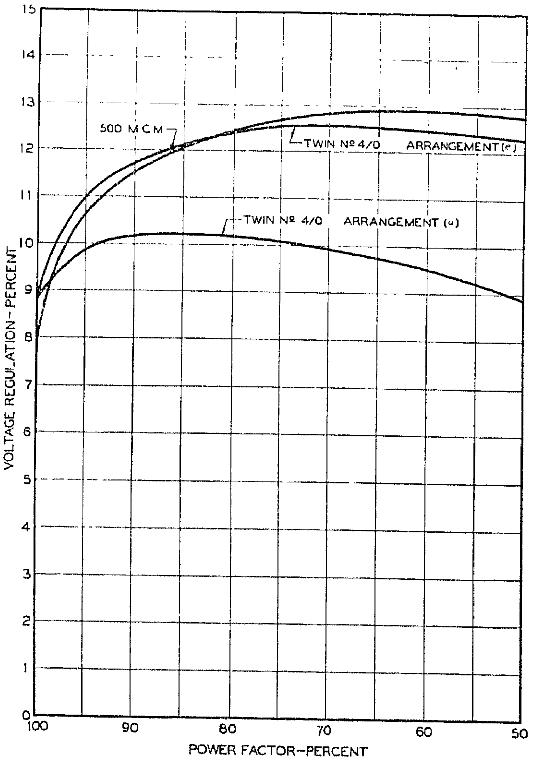

FIG. 4—VOLTAGE REGULATION PER THOUSAND CIRCUIT FEET WITH LOAD CURRENT OF 400 AMPERES

For two arrangements of twin circuits of No. 4/0 cable and for a single circuit of 500,000-cir. mil cable

## TEST RESULTS WITH SINGLE CIRCUITS AND TWIN CIRCUITS MADE UP WITH SINGLE-CONDUCTOR CABLE

In order to check the differences which a theoretical study indicated to exist between single circuits and twin circuits of single-conductor cable a test set-up was made with 500 circuit feet of 3 single-conductor cables of 500,000-cir. mil and No. 4/0 neutral for the single circuit and 500 circuit feet of 7 single-conductor cables of No. 4/0 size for the twin circuit arrangements.

TABLE I

| Arrangement | Impedance Calculated | | 10$^{-6}$ ohms/ft. Measured | | Measured percent unbalance in current between conductors |
|---|---|---|---|---|---|
| | *R* | X | *R* | X | |
| a | 25.70 | 15.79 | 25.76 | 16.96 | 2.0 |
| b | 25 70 | 17.60 | 28.10 | 17.76 | 14.8 |
| c | 25.70 | 21.50 | 27.16 | 23.04 | 13.0 |
| d | 25.70 | 23.90 | 29.16 | 24.20 | 1.6 |
| e | 25.70 | 27.74 | 30.40 | 28.18 | 14.8 |
| f* | 22.80 | 31.20 | 25.22 | 32.16 | |
| g | | | 28.60 | 17.74 | 10.1 |
| h | | | 27.12 | 17.48 | 6.0 |
| i | | | 29.80 | 24.80 | 5.6 |
| j | | | 28.96 | 18.00 | 13.8 |
| k | | | 27.22 | 18.28 | 5.8 |
| l | | | 29.72 | 24.42 | 12.7 |

*Arrangement (f) is single circuit of 3 single-conductor 500,000-cir. mil cables and a 4/0 neutral.

All the other arrangements are twin circuits of 6 single-conductor 4/0 cables and a 4/0 neutral.

Various groupings of phase relations were measured in the several arrangements as indicated in Fig. 3 in order to check the calculated constants.

Test results indicated agreement with the calculated values within the precision of measurements used in the test and are summarized in Table I. It will be noted that there is an effective increase in the resistance of the conductors in single-conductor lead sheathed cable due to sheath losses and these are not entirely negligible in the larger sizes of cable even when the 3 cables are mutually tangent. These sheath losses give an apparent increase in conductor resistance of 5.5 per cent for 500,000-cir. mil single-conductor cables, 2.3 per cent for 350,000-cir. mil single-conductor cables and 0.7 per cent for No. 4/0 single-conductor cables.

## SPACED CONDUCTORS

From the foregoing, it follows that busses and separated conductors (such as are generally used in temporary construction service) have inherently high reactance. The use of these configurations should be avoided where good voltage regulation is required unless the circuit length is short.

## REGULATION EFFICIENCY

The regulation efficiency, that is, the amperes per thousand circular mil, which may be carried in a given cable to give one per cent voltage regulation per 100 circuit feet on a three-phase four-wire 120/208 volt circuit for the various types of construction and sizes of cable is shown in Fig. 5. It will be noted for any given type of cable construction that the regulation efficiency improves with the smaller wire sizes of cable, and that by types of cable construction, the concentric type has the greatest efficiency, the sector type the next better efficiency and single conductor the poorest efficiency, with the twin circuits of single-conductor cable lying between the values for single-conductor cable and sector type of cable.

While the concentric type of cable construction has the highest regulation efficiency, it is also the most expensive. Based upon manufacturers' figures (market value of copper and lead being 6 cents and 3 cents respectively), the following table indicates the relative cost for the various sizes and type of cables where 1/0 single-conductor rubber insulated lead sheathed cable has been taken as the base at 100 per cent.

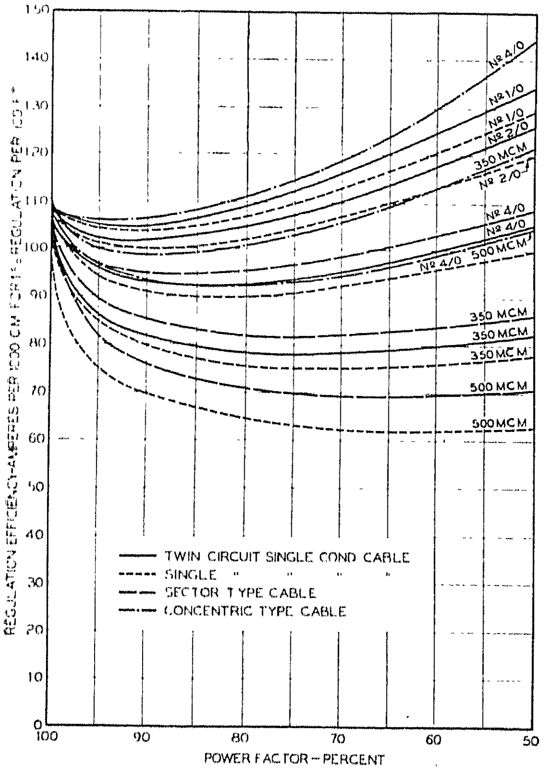

FIG. 5—REGULATION EFFICIENCY OF VARIOUS TYPES OF CABLE

RELATIVE COSTS OF CABLE IN PER CENT PER UNIT CIRCUIT LENGTH

| Cable size | *Single cond. cable (3 cables) | †Sector cable | †Concentric cable |
|---|---|---|---|
| 1/0 | 100 | 148 | 181 |
| 2/0 | 116 | 173 | 213 |
| 4/0 | 140 | 243 | 262 |
| 350,000 cir. mil | 221 | 365 | 360 |
| 500,000 cir. mil | 300 | 470 | 455 |

*Low-tension cable rubber-insulated lead sheathed.

†Low-tension cable 3-conductor paper-insulated lead sheathed.

Combining the data of the regulation efficiency and the cost of cable, trend curves are obtained which show the cost per unit of carrying capacity for unit regulation with various power factors. These curves are shown in Fig. 6. These data indicate that there is a spread of some 85 per cent in cost for the various cable sizes usually found in practise to give the same regulation per unit length of circuit.

## COST OF CABLES INSTALLED

The previous cost data includes only the cost of cable, but the true economic study of relative cost should be based on cables installed and spliced particularly where the installation cost may be somewhat different for the different types of cable construction and arrangement. Based upon field studies it is indicated that the pulling in charges for twin circuits, six single-conductor cables and neutral, in the same duct is about 10 per cent greater than the charges for four single-conductor cables or for a multi-conductor cable.

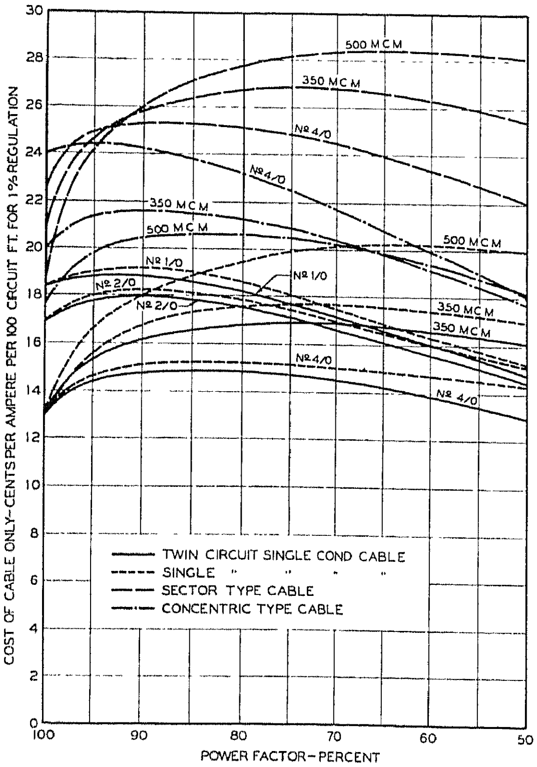

FIG. 6—COST OF CURRENT CARRYING CAPACITY OF VARIOUS TYPES OF CABLE

The relative costs of splicing single circuits of single-conductor cable and multi-conductor cable are as follows:

| Cable size | Relative cost of splicing in per cent |
|---|---|
| 1/0 | 100 |
| 2/0 | 111 |
| 4/0 | 122 |
| 350,000 cir. mil | 132 |
| 500,000 cir. mil | 140 |

Field studies on the splicing of twin circuits indicated that this cost was about 50 per cent greater than for the splicing of single circuits.

With the cost of installing and splicing cable added to the cost of the cable a new set of trend curves is obtained which shows the total cost per unit circuit length to give equal regulation at various power factors. See Fig. 7.

It is also of interest to know to what extent the variations in the metal market may be reflected in the cost of regulation of the various types and sizes of cable. A set of curves has been prepared in Fig. 8 showing this cost based on copper and lead prices of 18 cents and 6½ cents per lb. respectively.

## CONCLUSIONS

The economic comparisons as indicated in Figs. 7 and 8 show that with low metal market prices twin circuits with No. 4/0 single-conductor cables provide the most economical distribution unit. At relatively high metal market prices both 350,000-cir. mil and 500,000-cir. mil concentric type cable show a slightly lower cost than twin circuit of No. 4/0 cables. While these concentric type cables might prove adaptable to construction which is not required to be worked alive it appears that for low-tension mains cable the twin circuits of No. 4/0 cable hold an economic advantage whether the metal market be high or low.

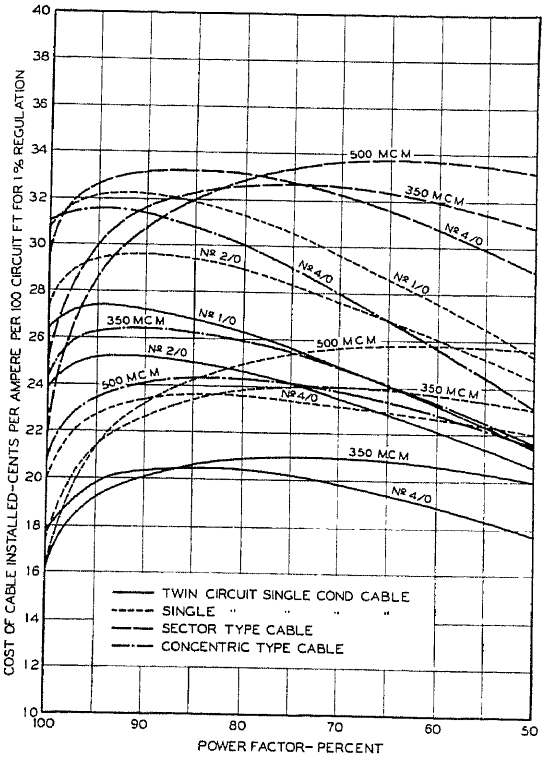

Fig. 7—Cost of Current Carrying Capacity of Installed Cable of Various Types Based on Low Metal Market Prices

Field experience has indicated that it is practical to keep relative phase arrangements during pulling in and splicing of the cable and thereby are able to secure the maximum economic use of the twin circuit main. The comparative cost of installed cable between the most favorable and least favorable arrangement of twin circuits of No. 4/0 cable and a single circuit of 500,000-cir. mil cable is shown in Fig. 9. Actual investment per circuit foot is substantially the same for either of

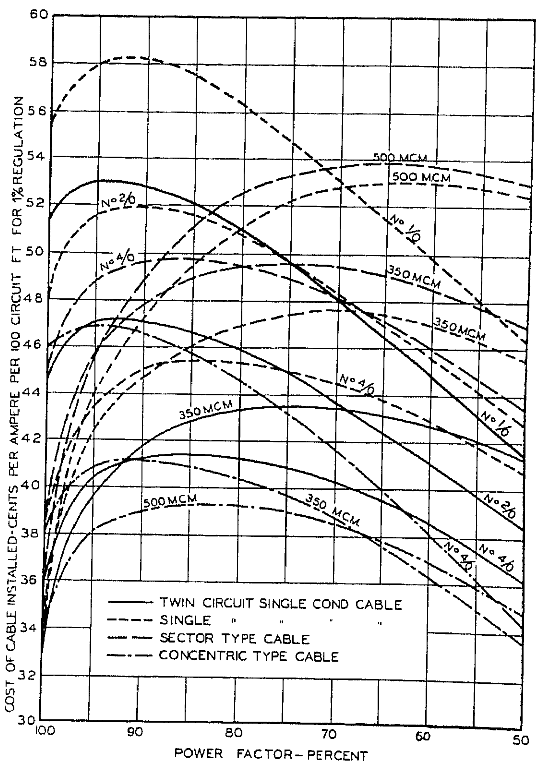

Fig. 8—Cost of Current Carrying Capacity of Installed Cable of Various Types Based on High Metal Market Prices

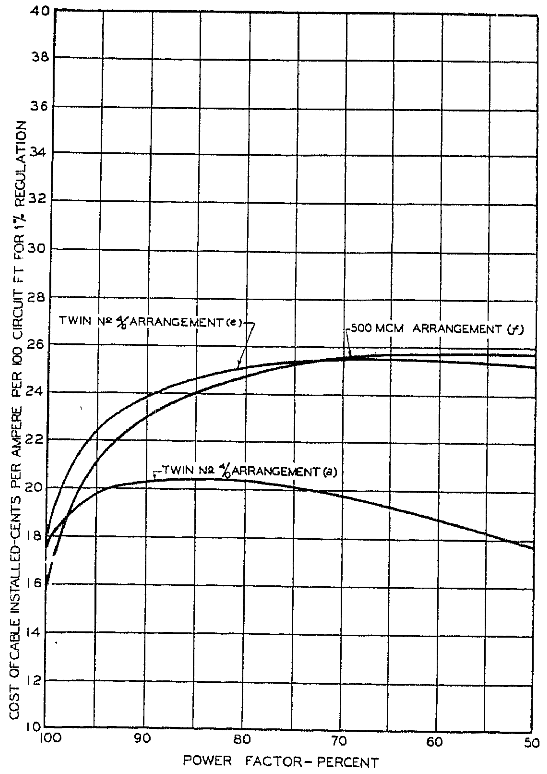

Fig. 9—Effect of Phase Arrangements on the Cost of Current Carrying Capacity

these two types of construction. It will be noted that at low power factor even the most unfavorable arrangement of twin circuits is preferable to a single circuit.

In all the theoretical material included in this paper the reactance values used have been calculated on assuming the cables to lie mutually tangent. This condition has been found to hold to a fair degree of approximation in the case of twin circuits installed in a common duct but single circuits usually show an appreciable increase in reactance over the calculated values for close spacing due to their spreading out in the duct.

## Appendix I

Relations between load current, power factor, circuit impedance and voltage regulation.

The voltage regulation for any circuit may be expressed as

$$\gamma = \frac{E_i - E_r}{E_r} \tag{1}$$

where

$E_i$ = impressed voltage
$E_r$ = received voltage
$i$ = load current
$\cos\theta$ = power factor of load
$r$ = circuit resistance
$x$ = circuit reactance
$z$ = circuit impedance

The impressed voltage may be expressed in terms of the received voltage and line drop as

$$E_i = \sqrt{[E_r + i(r\cos\theta + x\sin\theta)]^2 + [i(x\cos\theta - r\sin\theta)]^2} \tag{2}$$

By combining equations (1) and (2) an expression for load current is obtained in terms of voltage, power factor, impedance and regulation

$$i = \frac{E_r\,\{\sqrt{(r\cos\theta + x\sin\theta)^2 + z^2[(1+\gamma)^2 - 1]} - (r\cos\theta + x\sin\theta)\}}{z^2} \tag{3}$$

The minimum load current ($i_{min}$) which obtains for a given value of voltage regulation is at a power factor such that $\theta = \tan^{-1} x/r$ and may be expressed as

$$i_{min} = \frac{E_r\,\gamma}{z} \tag{4}$$

By combining equations (3) and (4) an expression for the ratio of load currents is obtained as a function of load power factor, circuit impedance and voltage regulation

$$i/i_{min} = \frac{\sqrt{(r\cos\theta + x\sin\theta)^2 + z^2[(1+\gamma)^2 - 1]} - (r\cos\theta + x\sin\theta)}{z\gamma} \tag{5}$$

## Appendix II

### 60-Cycle Reactance of Cable

1. The reactance per conductor of 3 single conductors carrying balanced three-phase currents, for equal spacing, is

$$x = 0.0529 \log_{10} \frac{s}{a} + 0.00574 \text{ ohms per thousand feet}$$

where

$a$ = radius of conductor
$s$ = distance between centers of conductors

2. The reactance per conductor of triple concentric cable for this study was taken as the average of values obtained from the following:

(a) Between inner and center conductors and between inner and outer conductors.

$$x = 0.0529 \log_{10} \frac{b_1}{a_2} + 0.0115 \left( \frac{1}{2} + \frac{1}{3}\,\frac{a_2^2}{b_1^2} - \frac{1}{12}\,\frac{a_2^4}{b_1^4} + \ldots \right)$$

ohms per thousand feet

where

$a_2$ = outer radius of inner conductor
$b_1$ = inner radius of outer conductor

(b) Between center and outer conductors.

$$x = 0.01151 \left[ 4.606 \log_{10} \frac{b_1}{a_2} + \frac{4.606\, a_1^4}{(a_2^2 - a_1^2)^2} \log_{10} \frac{a_2}{a_1} + \frac{4.606\, b_2^4}{(a_2^2 - a_1^2)^2} \log_{10} \frac{b_2}{b_1} - \frac{a_1^2 + b_2^2}{a_2^2 - a_1^2} \right] \text{ ohms per thousand feet}$$

where

$a_1$ = inner radius in cm. of inner conductor
$a_2$ = outer radius in cm. of inner conductor
$b_1$ = inner radius in cm. of outer conductor
$b_2$ = outer radius in cm. of outer conductor

3. Reactance of twin circuits—while numerous arrangements of twin circuits are possible as has been indicated in Fig. 3 formulas are only included for the first five cases as these cover all the possible arrangements when the neutral conductor is maintained in the central position of the group.

Referring to Fig. 10 it will be noted that the conductors have been given numbers in order to simplify the subscript designation and each of the following equations gives the average 60-cycle reactance for the individual conductors. The following symbols are used

$a$ = radius of conductor
$S_{12}$ = distance between centers of conductors 1 and 2
$S_{13}$ = distance between centers of conductors 1 and 3 etc.

(a) Reactance of arrangement shown in Fig. 3a

$$x = 0.01149 \left[ 0.5 + 4.606 \log_{10} \frac{(S_{12}S_{23}S_{31})^{1/3}(S_{51}S_{61}S_{42}S_{62}S_{43}S_{53})^{1/6}}{a\,(S_{41}S_{52}S_{63})^{1/3}} \right]$$

$$= 0.0529 \log_{10} \frac{\sqrt{3}\,S_{12}}{2a} + 0.00574 \text{ ohms per thousand feet.}$$

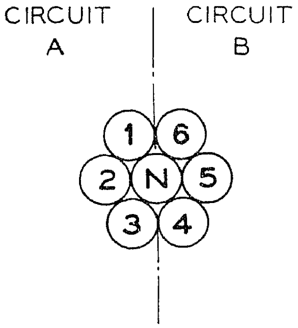

Fig. 10

(b) Similarly the reactance of arrangement shown in Fig. 3b

$$x = 0.0529 \log_{10} \frac{S_{12}}{a} + 0.00574 \text{ ohms per thousand feet.}$$

(c) Reactance of arrangement shown in Fig. 3c

$$x = 0.0529 \log_{10} \frac{\sqrt{2}\,S_{12}}{a} + 0.00574 \text{ ohms per thousand feet.}$$

(d) Reactance of arrangement shown in Fig. 3d

$$x = 0.0529 \log_{10} \frac{\sqrt{3}\,S_{12}}{a} + 0.00574 \text{ ohms per thousand feet.}$$

(e) Reactance of arrangement shown in Fig. 3c

$$x = 0.0529 \log_{10} \frac{\sqrt{2}\,\sqrt{3}\,S_{12}}{a} + 0.00574 \text{ ohms per thousand feet.}$$

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1. "The Theory of Alternating Currents," Alexander Russell, Vol. I, Second Edition, Chap. 2.

2. "Electrical Characteristics of Transmission Circuits," William Nesbit.

3. "The Impedance and Power Losses of Three-Phase Overhead Lines," P. D. Morgan and S. Whitehead. *Jl. of I.E.E.*, Vol. 68, p. 367, 1930.

# Traveling-Wave Voltages in Cables

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**Synopsis.**—*The problem of lightning protection of cables is more active at the present time than it has been in the past. This is due largely to the fact that cables of higher voltage connected directly to overhead lines are becoming very common; cables in the form of short sections are especially liable to need protection. The cost of the cable, the importance of the line from the operating standpoint, and the cost of protective equipment all enter into the picture.*

*In the present paper the factors which determine whether or not a cable will require protective equipment are discussed, and new and simplified formulas, representing with considerable precision any of the standard coordinating waves are developed. These formulas can be used for open-ended cable lines, or cable sections in transmission lines. Where cables terminate in station apparatus, the assumption of an open-circuited cable end may be safely used, since it always gives a calculated value of voltage that is somewhat above the true value. The effect of cable length and surge impedance and of line surge impedance are illustrated in detail. Tentative data on the impulse strength of cable insulation are also included.*

## INTRODUCTORY

In the earlier days of the electrical industry, comparatively little attention was paid to the protection of cables against lightning surges. Where cable lines were not connected to overhead lines, or where they were connected to such lines through transformers, special devices for the protection of cables were unnecessary, since the lightning surges impressed on such cables were seldom if ever of great severity. Furthermore, the high impulse ratio of cable insulation, together with the inherent tendency of cables, especially long ones, to reduce the magnitude of an entering wave to a relatively low value, has tended to make cables self-protecting. These factors still make protection unnecessary in many cases.

During the last decade, however, the maximum voltage at which cables have been successfully operated in commercial service has steadily increased; and there is reason to believe that this voltage will increase yet further in the future. This fact has resulted in an increasing use of short cable sections on high tension transmission lines; both at the end of a line, where overhead transmission is often impractical, and at points along the length of a line. Such links, being short, are not necessarily self-protecting. Again, the great advances made during this period in the art of cable manufacture have resulted in a considerable increase in the life of cables, and in their dielectric strength at operating frequencies; this improvement has been greater than the corresponding improvement in impulse strength. Finally, the cost of a high-voltage cable section is by no means negligible, and its importance from the operating standpoint is usually very great.

On the other hand, the cost of high-voltage protective equipment is often an appreciable item in the total cost of the cable section or cable line. It becomes increasingly important, therefore, to determine with some precision just when such equipment is required, and when it can safely be dispensed with.

The movement for the coordination of insulation which is at present on foot makes it particularly desirable to insure that a cable shall not prove to be a weak link in a system. It is because of this movement that formulas have been developed in terms of exponential wave shapes which approximate closely to the actual shapes of the coordinating waves. These formulas, incidentally, afford a method of calculation which is very much simpler than the "step-by-step" method usually used for such work.‡ Moreover, calculations can be made by these formulas in a much shorter time.

The factors which determine whether a cable needs lightning protection or not are as follows:

a. The magnitude of the incoming wave. This is usually limited by the impulse flashover of the line insulation or cable terminal, or possibly by a coordinating gap.

b. The effect of the cable and line surge impedances on the traveling wave.

c. The effect of the impedance at the far end of the cable.

d. The length of the cable, and its dielectric constant.

e. The impulse strength of the cable.

These last four factors are discussed in more detail in the following paragraphs.

## EFFECT OF THE CABLE ON THE TRAVELING WAVE

When a traveling wave on an overhead line reaches a cable, a wave of reduced voltage passes into the cable. This reduction is due to the fact that the surge impedance of a cable is less than that of an overhead line.

In a traveling wave the electrostatic energy is equal to the electromagnetic energy and the constants of a cable are such that the voltage of a traveling wave has a lower ratio to the current than in the case of a wave on an overhead line. After the wave enters the cable there are voltage and current reflections back and forth from each terminal. If the length of the original wave is great enough there will be several superimposed waves at each point in the cable. The sum of these several waves will be dependent upon the shape of the original wave as well as the reflection from each end of the cable.

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*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

‡The "step-by-step" method is successfully used by Beck (Bibliography, reference 1) and other writers.

The reflection at the cable terminal depends upon the surge impedances of the cable and of the connected line or apparatus. In this paper, calculated values of voltage are given for a range of cable surge impedance from 20 to 150 ohms and line impedances of 300 and 500 ohms. The calculations include the case of similar lines connected to each end of the cable, and the case of a line connected to one end of the cable only and a free terminal at the other, which is the case giving the highest voltage. The traveling wave is assumed to enter at the "near" end of the cable and the voltage at the "far" end calculated, since in general the maximum voltage will be found at that end. Reduction of the wave by cable losses was neglected, as tests have shown the losses to be small in 500- and 1,000-foot lengths of cable.

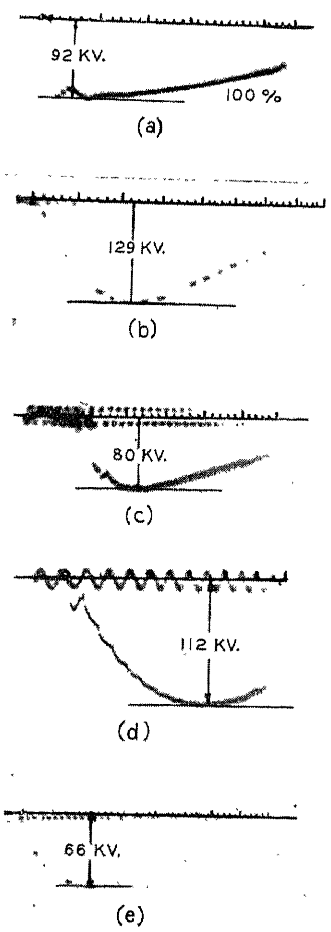

FIG. 1—OSCILLOGRAMS OF TRAVELING WAVE VOLTAGES MEASURED AT "FAR" END OF CABLE

(a) Line wave
(b) "Far" end of 500-ft. cable open at "far" end
(c) "Far" end of 500-ft. cable between two lines
(d) "Far" end of 1,000-ft. cable open at "far" end
(e) "Far" end of 1,000-ft. cable between two lines

## TYPICAL WAVES USED IN CALCULATIONS

Three different waves have been used in various coordination studies. They are the ½-5, the 1-10 and the 1 ½-40, in which the first figure is the time in microseconds to reach crest, and the second figure the time to reach half value on the tail of the wave. However, since both tests and calculation show that short wave fronts do not greatly affect the ultimate voltage resulting in the cable, and since turn-to-turn stresses in apparatus due to steep wave fronts are not being considered here the mathematical treatment of the problem in this paper has been simplified by using the 0-5, 0-10 and 0-40 waves. The waves have respectively the following formulas: $E\epsilon^{-.138t}$, $E\epsilon^{-.0692t}$ and $E\epsilon^{-.0173t}$, and will give slightly higher values for ultimate cable voltage than would be obtained from the first mentioned waves.

With these waves entering the cable the voltage at the cable terminals will rise to its maximum value and then decrease in a series of steps by successive reflections, each step having a vertical front. Under these conditions, it is possible to derive a simple formula for the maximum voltage at either cable terminal for the *n*th step, and also to determine the step at which the voltage will be a maximum (Fig. 6). This method was used because the principal interest in this paper is the maximum value to which the voltage rises in the cable rather than its rate of rise. (See Appendix I.)

## COMPARISON WITH FIELD TESTS

Results obtained by the above method check closely the field measurements obtained by Messrs. McEachron, Hemstreet and Seelye, in the Michigan tests on cables.[2] Oscillographic measurements from the Michigan tests are shown in Fig. 1. The following table gives the relation between the calculated and measured values for approximately the same conditions. The line surge impedance was 500 ohms, the cable impedance 50 ohms and a 2-50 wave arriving over the line.

TABLE I

| | Measured | Calculated |
|---|---|---|
| Line to 500 ft. cable open at far end | 142% | 150% |
| Line to 1,000 ft. cable open at far end | 120% | 124% |
| Line to 500 ft. cable to line | 87% | 82% |
| Line to 1,000 ft. cable to line | 72% | 74% |

## EFFECT OF WAVE SHAPE

As pointed out, the voltage resulting in the cable is dependent on the shape of the incident wave. This is shown in Fig. 2 where voltages at the "far" end resulting from the three waves are plotted for lengths of cable up to 20 microseconds.* The line impedance was taken as 500 ohms and the cable impedance 50 ohms. The "near" terminal of the cable is connected to the over-

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2. For numbered references see Bibliography.

*See Appendix II.

head line and the "far" terminal is free, *i.e.*, having no electrical connections. To make the curves general, the cable length is plotted in microseconds since the wave propagation velocity varies in different cables. The length of the cable in microseconds is approximately equal to the cable length in thousands of ft. multiplied by $\sqrt{K}$, the sq. root of dielectric constant of the cable insulation. This relation is due to the fact that the propagation velocity of electric waves is inversely proportional to the sq. root of the permittivity or dielectric constant of the insulating medium.

It may be noted (Fig. 2) that cable voltage is greater for the waves which decrease more slowly with time. This difference is more pronounced for the shorter lengths of cables. For example, in a two-microsecond cable which might be approximately 1,100 ft. in length, a 0-40 wave rises to 117 per cent, a 0-10 wave rises to 72 per cent and a 0-5 wave rises to 54 per cent. These values are referred to the crest of the incident wave or original wave arriving over the line, which is 100 per cent.

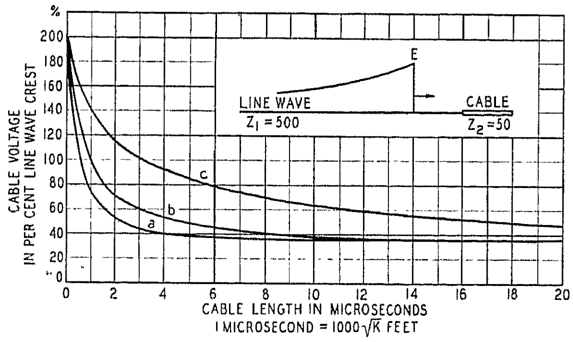

Fig. 2—Maximum Voltage at "Far" End of Cable

Resulting from (*a*) 0-5, (*b*) 0-10 and (*c*) 0-40 line waves. Cable open at "far" end

Although the curves cover a range of lengths up to 20 microseconds only, it should be noted further that where the cable is sufficiently long the voltage at the "far" end is equal to the first entering wave plus its reflection, the effect of further reflections being negligible. Since in this case the terminal at the "far" end of the cable is disconnected, the minimum value of voltage is twice the first entering wave.

### Effect of Line Surge Impedance

To show how surge impedance of the line affects the cable voltage, curves are given for two values of line impedance, 300 and 500 ohms, with the 0-40 wave and 50-ohm cable impedance as shown in Fig. 3. These curves show that a higher surge impedance of the line results in a lower voltage in the cable. The effect is greater with longer cables.

### Effect of Cable Surge Impedance

Fig. 4 shows how cable surge impedance affects the resulting voltage. In this case the cable impedance was varied from 20 to 150 ohms while the other factors were kept constant. In practise the cable surge impedance varies over a relatively greater range than the line impedance. These curves show a wide difference of cable voltage for the eight values of cable surge impedance examined. For example, with an 8-microsecond cable, the voltage varies from 40 per cent to about 120 per cent for impedances of 20 and 150 ohms respectively.

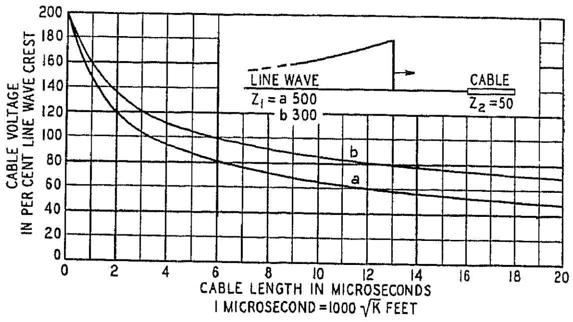

Fig. 3—Maximum Voltage at "Far" End of Cable

Resulting from a 0-40 wave on lines of 300 and 500 ohms surge impedance Cable open at "far" end

### Effect of Impedance at "Far" End of Cable

Where a line is connected at the "far" end of the cable, as shown in Fig. 5, the reflected voltage, and therefore the resultant voltage, is less than that for an open-end cable where full reflection occurs. This may be seen by comparing the curves in Fig. 5 with the corresponding curves in Fig. 4. Take the case of a 20-microsecond cable of 30 ohms surge impedance, the voltage is about 33 per cent in Fig. 4 and about 28 per cent in Fig. 5. This difference is small. But if the cable length is decreased to 2 microseconds, the cable voltage is about 97 per cent in Fig. 4 and nearly 63 per cent in Fig. 5. These curves show that the impedance connected at the "far" end of the cable is more important in the case of shorter cables. As the cable length approaches zero, the cable voltage approaches 100 per cent in Fig. 5 where the "far" end of the cable is connected to a line, and 200 per cent in Fig. 4 where the "far" end of the cable is an open circuit. When

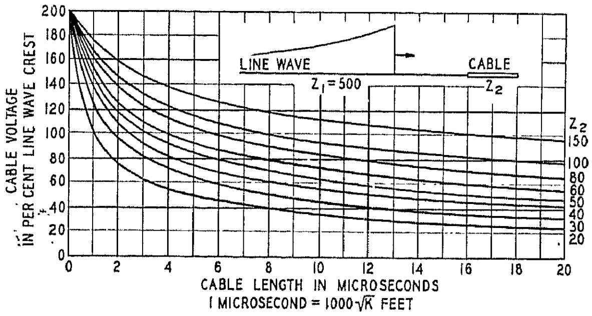

Fig. 4—Maximum Voltage at "Far" End of Cables of Various Surge Impedances

Resulting from a 0-40 wave on a line of 500 ohms surge impedance. Cable open at "far" end apparatus is connected to the "far" end of the cable and has a high impedance compared with the cable, the condition is approximately that of open circuit at the "far" end. This assumption always gives a value of voltage in the cable which is slightly higher than the value which actually will occur where the cable terminates in station apparatus.*

### IMPULSE STRENGTHS

Data on the impulse strength of cables are very meager at the present time, although a test program is under way which should go far in extending the knowledge now available. The curve given in Fig. 7 is based on somewhat limited data, taken with the three coordinating waves previously referred to. The curve actually represents an average value of all the data obtained, since it appeared from the tests that the difference in wave shape did not greatly affect the value of breakdown. The curve is suggested tentatively for use in connection with the present formulas as a guide to a decision as to whether protection is or is not required. It should, of course, be used with a suitable factor of safety. The data was taken on impregnated paper cable, of both the solid and the oil-filled types; and it may be used with a good degree of confidence for these types of cables. No corresponding data were taken on varnished cambric or rubber cable. Fig. 7 should therefore be used with great caution when considering these types of cable.

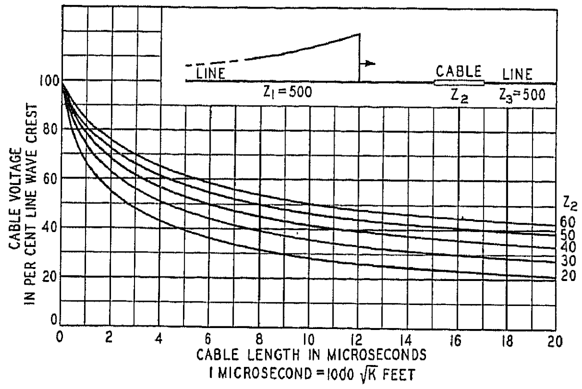

FIG. 5—MAXIMUM VOLTAGE AT "FAR" END OF CABLES OF VARIOUS SURGE IMPEDANCES

Resulting from a 0-40 wave on a line of 500 ohms surge impedance. Cable connected between two lines

Tables giving line flashover values for various numbers of standard 5¾ by 10 in. disk insulators have been published in a number of places by F. W. Peek, Jr.[3,4] The impulse strength of wood pole lines may be estimated from the length of wood in circuit to ground.[5,6]

### CABLE SURGE IMPEDANCE

The surge impedance of the cable can be determined from the formula.

$$Z\text{ (cable)} = \frac{G}{0.0169\, n\sqrt{K}}$$

Where

$K \doteq$ dielectric constant of cable insulation.
$n$ = number of conductors.
$G$ = geometric factor.

Curves of $G$ have been published in several places by Simmons.[6,10] Table II gives working values for the cable dielectric constant.

TABLE II

| Type of insulation | Working value of $K$ |
|---|---|
| Paper (solid) | 3.5 |
| Paper (oil filled) | 3.4 |
| Varnished cambric | 4.2 |
| Rubber | 4.4 |

Dielectric losses in the cable were neglected when preparing the curves. Results from the Michigan tests indicate that for short cables this loss is not great enough to greatly affect the resulting voltages. However, for long cables it is possible that attenuation of the voltage wave due to dielectric losses will result in lowering maximum voltage. Further test data are needed to determine how much attenuation alters the problem.

### LIMITING HIGH VOLTAGE IMPULSES

Taking the crest voltage of the assumed incident waves as limited by the lightning flashover of the connected line, these curves and formulas may be used to determine the maximum voltage to which a cable and connected apparatus will be subjected. This value can be compared with the insulation strength of the cable, pothead, and connected apparatus to determine the protective requirements.

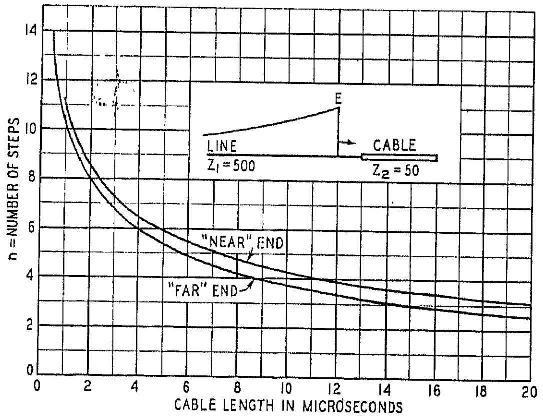

FIG. 6—NUMBER OF STEPS TO REACH MAXIMUM VOLTAGE AT ENDS OF CABLE AS FUNCTION OF CABLE LENGTH

Cable open at "far" end

Where a cable of comparatively low voltage rating and correspondingly low impulse strength is connected to a wood pole line having high insulation level, the application of lightning arresters at the junction of cable and line becomes especially important, since without an arrester the first transmitted wave in the cable may exceed the cable strength. Assuming that the wave entering the cable is thus limited by an arrester at the line end of the cable, it may still be necessary to use an arrester at the "far" end of the cable to prevent further rise of voltage by reflection, particularly if connected apparatus at the "far" end would not withstand reflection (approaching double value) of the voltage wave passed by the arrester at the junction of cable and line.

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*The matter of terminal impedances has been covered in more detail by Bewley. See Bibliography 12.

For shorter lengths of cables where several reflections occur in the cable before reaching a maximum value, the crest value of voltage will be approximately the same at both ends of the cable. Under such conditions the application of a single arrester may be sufficient protection. Where there is apparatus at the "far" end of the cable, location of the arrester at that end will conform to the general recommendation that the arrester be located within 50 circuit feet of the apparatus for circuits below 69 kv. and within 100 circuit feet for circuits above 69 kv.

## PRACTICAL EXAMPLE

The application of the curves can be illustrated by calculation of a specific problem. A wooden pole line having an impulse flashover of approximately 1,500 kv. is connected to a 2,000-foot section of belted-paper-insulated three-conductor cable terminating in a substation.

It is assumed that equal waves are arriving on each conductor of 1,500 kv. Under these conditions the surge impedance of each line is taken as 500 ohms. The cable has the following characteristics:

| | |
|---|---|
| Paper insulation thickness: | |
| a. Between conductors | 0.16 in. |
| b. Between conductor and sheath | 0.12 in. |
| 0000 conductors (diameter) | 0.46 in. |
| Impulse strength | 200 kv. |
| Geometric factor (Simmons) | 1.2 |
| Dielectric constant | 3.5 |

The surge impedance of the three conductors in the cable in parallel is:

$$Z_c = \frac{1.2}{0.0169 \times 3 \times \sqrt{3.5}} = 12.6$$

or 38.0 ohms per conductor.

The cable length in microseconds is:

$$2 \times \sqrt{3.5} = 3.75 \text{ microseconds}$$

Referring to Fig. 4 the maximum unprotected cable voltage as built up by wave reflections is given as 83 per cent of the traveling wave voltage on the line which was 1,500 kv. Therefore, the voltage in the cable would be 1,245 kv. Considering that the impulse strength of the cable is approximately 200 kv., protective equipment for the cable is necessary.

The first transmitted wave at the junction of the cable and line may be obtained from the formula:

$$E_2 = 2E_1 \frac{Z_2}{Z_1 + Z_2} = 212 \text{ kv.}$$

Since the cable strength is below this value of the first entering wave, an arrester is warranted at the junction of the cable and line. The first transmitted wave through the cable will approach double value at the "far" end of the cable when the "far" end is open circuited or connected to a transformer or other apparatus of high impedance. An arrester located at the junction of the overhead line and cable, limits the transmitted voltage, but the voltage appearing at the "far" end approaches double arrester voltage. This value should be compared with the strength of connected apparatus and also with cable and pothead strengths to determine the necessity for an arrester at that point.

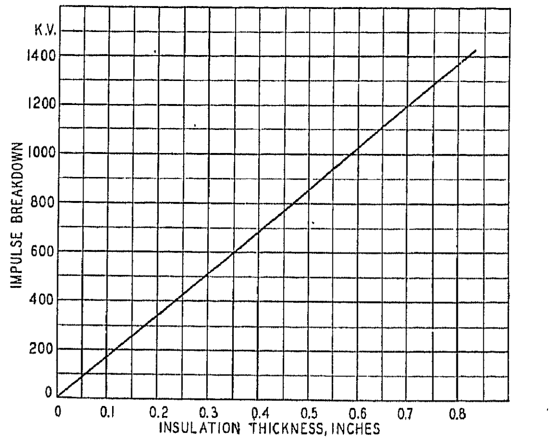

FIG. 7—APPROXIMATE WORKING VALUES OF IMPULSE BREAKDOWN OF CABLE INSULATION

From data on impregnated paper, solid and oil-filled single-conductor, and type h three-conductor cables

There may be cases where the cable strength and pothead flashover are somewhat greater than the first transmitted wave, and the point of weakest insulation is in the connected apparatus. In such cases, an arrester should be used to limit the voltage to a safe value for the apparatus, and located at the apparatus end of the cable. In this case additional protection would not seem warranted at the junction of the line and cable except for the case of direct stroke at or near that point.

There are so many ramifications to the problem of cable protection that it becomes very difficult to formulate general rules for their protection which will cover all cases.

However, it may be said that where low-voltage cables with corresponding low-impulse strength are connected to highly insulated lines such as a wooden pole structure having ungrounded hardware, safe practise requires the use of adequate arrester protection. Problems where the comparative strengths and lengths have other values may be examined to determine the degree of protection warranted for any particular installation in question.

## Appendix I

Assume a wave of vertical front and sloping tail represented by $E\epsilon^{-BT}$ and traveling on a line of surge impedance $Z_1$ into a cable of surge impedance $Z_2$ with a line of surge impedance $Z_3$ at the "far end." The front of the first wave entering the cable is: $\dfrac{2Z_2}{Z_1 + Z_2}E$.

This front is reflected at the "far end" of the cable, producing a total instantaneous voltage $AE$ where

$$A = \frac{2Z_2}{Z_1 + Z_2}\left[1 + \frac{Z_3 - Z_2}{Z_3 + Z_2}\right]$$

The reflected wave travels back to the "near end" of the cable where it is reflected again, thus producing a second entering wave which is $M$ times the first wave and which results in an additional voltage at the far end of $M$ times that produced by the first wave. Similarly there is a third entering wave, $M$ times the second wave or $M^2$ times the first wave, etc. $M$ is the product of the two reflection factors.

$$M = \frac{Z_1 - Z_2}{Z_1 + Z_2} \cdot \frac{Z_3 - Z_2}{Z_3 + Z_2}$$

and is always less than 1. Therefore, each entering wave is less than the preceding entering wave, part of the wave having been lost by transmission back into the line. Each of these waves has a vertical front and falling tail. Thus the voltage at the "far end" of the cable rises and then falls in a series of steps. At each step the voltage rises vertically and then falls until the next step. Therefore, the maximum voltage occurs at the beginning of one of these steps. If $T$ is the time required for a wave to travel twice the length of the cable, then at the beginning of the $n$th step the voltages of the preceding waves at the "far end" of the cable have been reduced by the factors $\epsilon^{-BT}$ $\epsilon^{-2Bt}$ etc. Therefore the total voltage at the $n$th step is:

$$E_{23}(n) = AE[M^{n-1} + M^{n-2}\epsilon^{-BT} + \ldots M^{n-n}\epsilon^{-(n-1)BT}]$$

This series is equal to the equivalent fractional expression:

$$E_{23}(n) = AE\frac{M^n - \epsilon^{-nBT}}{M - \epsilon^{-BT}}.$$

The formula value for $n$ to give maximum value of $E_{23}$ is determined in the usual way:

$$\frac{d}{dn}(M^n - \epsilon^{-nBT}) = 0$$

$$n\ (\text{for max } E_{23}) = \frac{\log\dfrac{-BT}{\log M}}{BT + \log M}$$

If this value of $n$ is not a whole number, then the two nearest whole numbers should be tried to determine which gives the maximum value. Usually, but not always, the nearest whole number gives the maximum value. The time at which the maximum value occurs is found by multiplying $T$ by the number of steps. In the above formula log $M$ is negative since $M$ is always less than one.

The formula for $E_{12}$ at the near cable junction is derived in a similar way.

Let

$$F = \frac{Z_3 - Z_2}{Z_3 + Z_2}\ \text{reflection factor at far terminal}$$

$$A^1 = \frac{2Z_2}{Z_1 + Z_2}$$

Then the initial voltage is $A^1E$.

The voltage at the second step is:

$$A^1E\epsilon^{-BT} + A^1E(M + F)$$

The voltage at the $n$th step is:

$$\begin{aligned}E_{12}(n) &= A^1E[\epsilon^{-(n-1)BT} + (M + F)\epsilon^{-(n-2)BT} \\ &\quad + M(M + F)\epsilon^{-(n-3)BT} + \ldots + M^{(n-2)}(M + F)] \\ &= A^1E[\epsilon^{-(n-1)BT} + (M + F)\epsilon^{-(n-2)BT}(1 + M\epsilon^{BT} \\ &\qquad + M^2\epsilon^{2BT} \ldots + M^{n-2}\epsilon^{(n-2)BT})] \\ &= A^1E\left[\epsilon^{-(n-1)BT} + (M + \mathrm{F})\epsilon^{-(n-2)BT}\frac{1 - M^{(n-1)}\epsilon^{(n-1)BT}}{1 - M\epsilon^{BT}}\right] \\ &= A^1E\left[\frac{M^{n-1}(M + F) - \epsilon^{-nBT} - F\epsilon^{-(n-1)BT}}{M - \epsilon^{-BT}}\right]\end{aligned}$$

The value of $n$ for maximum $E_{12}$ is:

$$\frac{\log\dfrac{-BTM(1 + F\epsilon^{BT})}{(M + F)\log M}}{BT + \log M}$$

Fig. 6 shows how the value of $n$ varies with the cable length for case of a cable at the end of a line, the far end of the cable being open.

## Appendix II

The traveling wave energy passing a given point in the infinitesimal time $dt$ is:

$$EI\,dt = E\,dQ$$

$E$ = instantaneous voltage

$I$ = instantaneous current

The electrostatic energy that shifts from one side of this point to the other during time $dt$ and is associated with the infinitesimal length $ds$ is:

$$1/2\,C\,ds\,E^2 = 1/2\,E\,dQ \text{ since } Q = CE$$

Therefore, the electrostatic energy in a freely traveling wave is one-half the total energy and is equal to the electromagnetic energy.

$C$ = capacitance per unit length
$L$ = inductance per unit length

Then

$$1/2\, CE^2 = 1/2\, LI^2$$

$$E = I\sqrt{\frac{L}{C}} = IZ$$

where $Z$ = surge impedance

Since $ds = v dt$ where $v$ = velocity of propagation

$$EI\, dt = C\, ds\, E^2 = Cv\, dt\, E^2$$

$$v = \frac{I}{CE} = \frac{1}{CZ} = \frac{1}{\sqrt{LC}}$$

and

$$Z = \frac{1}{CV}$$

If $L_0$ is inductance when the permeability is one and $C_0$ is the capacitance when the permittivity is one, then

$$V_0 = \frac{1}{\sqrt{L_0 C_0}} = \text{velocity of light}$$

In cables the permeability is one but the permittivity or dielectric constant has the value $K$.

$$V = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{KL_0 C_0}} = \frac{V_0}{\sqrt{K}}$$

Since

$$Z = \frac{1}{CV}$$

$$Z = \frac{\sqrt{K}}{CV_0}$$

$V_0$ is approximately equal to 1,000 feet per microsecond (actually 984) and so if we let $C_1$ be the capacitance in microfarads per 1,000 ft. we have

$$Z = \frac{\sqrt{K}}{C_1} \text{ approximately}$$

This is a convenient formula for calculating the surge impedance of a cable.

In plotting curves involving traveling waves it is convenient to state the cable length in microseconds as the velocity varies in different cables. The actual length $S$ is equal to the length in microseconds $S_1$ times the velocity in feet per microsecond.

Therefore

$$S = S_1 \frac{1}{ZC_1}$$

$C$ = capacitance in $\mu$f. per 1,000 ft.
$S$ = length in 1,000 feet.

$$= \frac{S_1}{\sqrt{K}}$$

and

$$S_1 = S\sqrt{K}$$

also

$$S_1 = Z\, C_S$$

where

$C_S$ = capacitance of length $S$.

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3. *Lightning*, by F. W. Peek, Jr., A.I.E.E. TRANS., Vol. 50, p. 1077.
4. *The Effect of Transient Voltages on Dielectrics-IV*, by F. W. Peek, Jr., A.I.E.E. TRANS., Vol. 49, p. 1456.
5. *Lightning Investigation on Wood Pole Transmission Line*, by Pittman, Torok, A.I.E.E. TRANS., Vol. 50, p. 568.
6. *Cable Geometry and the Calculation of Current Carrying Capacity*, by D. M. Simmons, A.I.E.E. TRANS., Vol. 42, p. 600.
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10. "Underground Systems Reference Book," pp. 297, 298.
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12. *Traveling Waves on Transmission Systems*, by L. V. Bewley, TRANS. A.I.E.E., Vol. 50, p. 532.

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## Discussion

**Edward Beck:** The writer desires to register his accord with the observations of Messrs. Brinton, Buller, and Rudge about the improbability of low voltage cables connected to highly insulated lines such as those on wood poles being self-protecting; also those regarding the possibilities of high-voltage cables being self-protecting. As the authors remark, it may pay to examine specific installations for the degree of protection economically warranted. The writer has expressed such views in the reference cited in the bibliography and recently in the *Electric Journal*.

There is a phase of the behavior of traveling waves in cables which, so far as we are aware, has received little attention. The usual treatments of surges in cables consider the cable sheath grounded throughout its length. For this assumption the simple relations usually given are quite correct. It is not necessarily a fact, however, that in practise the cable sheath is grounded throughout its length. Often there may be a considerable ungrounded length of sheath between the entrance and the first sheath ground. It may even be the case that the sheath is entirely ungrounded or grounded through high resistance. The cable potentials in such cases are of practical importance. Some theoretical considerations led to the suspicion that a cable whose sheath is not grounded at the entrance may be subjected to high voltages internally.

The writer has made a series of tests on cables which shed some light on the subject. The cable set-up used was as shown in Fig. 1.

To lead up to the situation let us first consider a cable whose sheath is completely isolated from ground. Theoretically, such a cable should act very much like an open line with the same order of surge impedance and velocity of propagation since the presence of the ungrounded sheath has little effect on the distributed constants. It was found to be so by test. The measured surge impedance of the cable with ungrounded sheath was 492 ohms, and the velocity of propagation 890 feet per microsecond.

There should be no voltage across the cable insulation because the sheath will pick up by induction a voltage of the same order as the conductor voltage. The tests indicate that this is so, Fig. 2. At the far end the characteristic increase in voltage caused by reflection appears. There is still no potential difference between conductor and sheath. Such a cable needs no protection for itself, although apparatus connected to it does.

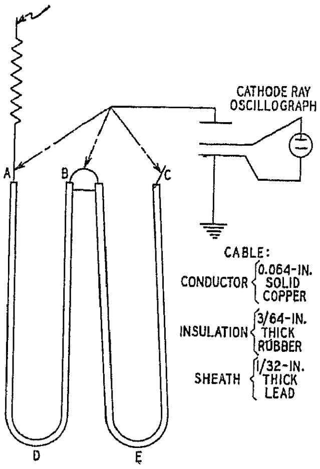
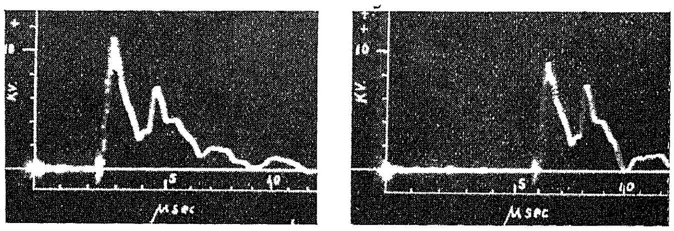

CATHODE RAY OSCILLOGRAPH
A
B
C
D
E
CABLE:
CONDUCTOR 0.064-IN. SOLID COPPER
INSULATION 3/64-IN. THICK RUBBER
SHEATH 1/32-IN. THICK LEAD

Fig. 1—Diagram of Connections for Cable Tests

$AB$ = 352 ft: $BC$ = 383 ft: $AD$ = 233 ft: $BE$ = 165 ft



Conductor voltage at $A$
Maximum = 10.7 kv

Sheath voltage at $A$
Maximum = 9 kv

Conductor voltage at $C$
Maximum = 17 kv

Sheath voltage at $C$
Maximum = 17.3 kv

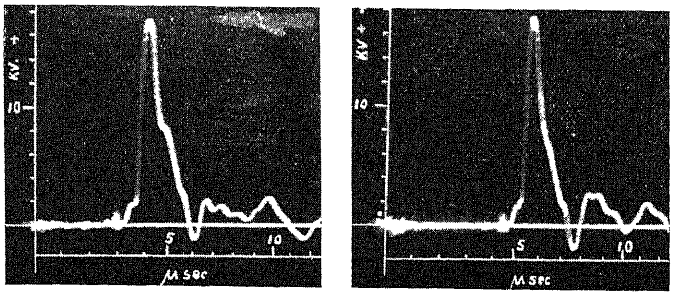
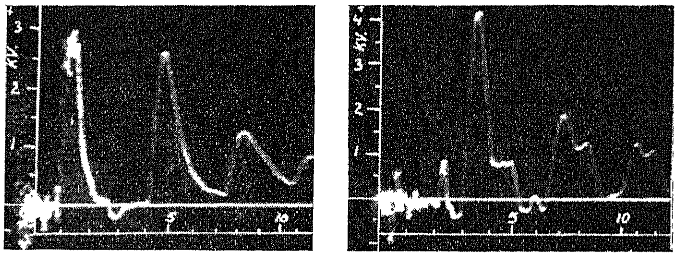


Fig. 2—Voltages With Cable Sheath Insulated From Ground

Now consider the sheath grounded at the entrance only, Fig. 3. The characteristic reduction in conductor voltage takes place, the maximum voltage being 2.7 kv instead of 10.7 kv. The surge impedance of the cable is now much less, measurements indicated 39 ohms. The velocity of propagation is also less, 450 ft per microsecond. The cable now acts in the usually considered manner. The conductor potential appears between conductor and sheath. At the far end, $C$, the usual reflections occur, the sheath potential however, remains zero except for extraneous disturbances. Thus such a cable acts like the cables with grounded sheaths usually discussed. Measurements at $B$, the midpoint, indicated similar effects. A cable grounded at the entrance acts very like one grounded throughout its length and its insulation will be subjected to potential.

Now let us consider the cable with its sheath grounded only at the far end $C$, Fig. 4. While the surge is traveling from $A$ to $C$, the cable acts as if the sheath were insulated, because the surge cannot tell that there is a ground at $C$ until it reaches $C$. There is no reduction in entering voltage, therefore, until the reflection produced at $C$ by the grounded sheath returns to $A$. The sheath potential at $A$ again is the same as the conductor voltage, as far as is apparent, so again there is no voltage on the cable insulation at $A$. At $C$ the sheath potential is zero because it is grounded, the voltage on the conductor is reduced below the incoming voltage measured at $A$ because the cable turns from an ungrounded to a grounded one, in other words, the change from open line to cable takes place at $C$. Potential develops between the conductor and sheath at $C$. An arrester between conductor and sheath at $A$ would do no good because it would not discharge since there is negligible potential difference between the conductor and sheath at $A$. This is important because it may easily appear offhand that an arrester between conductor and sheath would protect the cable regardless of grounding conditions. In the protection of distribution transformers, for instance, it is a fact that if the transformer insulation is shunted by arresters, it is protected regardless of grounds. This does not hold for cables. The point of greatest danger to the cable is where the sheath ground is, or at the far end if the conductor terminates there.



Conductor voltage at $A$
Maximum = 2.7 kv

Conductor voltage at $C$
Maximum = 4.2 kv

Sheath voltage at $C$

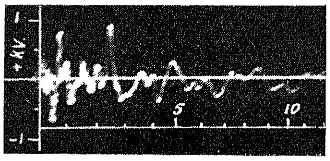


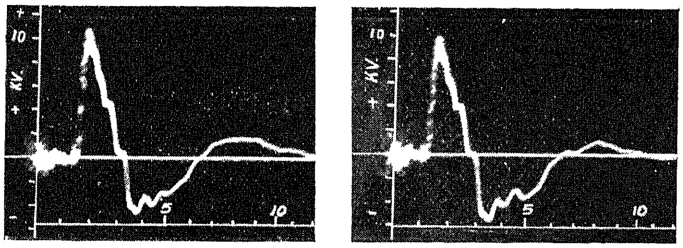
Fig. 3—Voltages With Cable Sheath Grounded at Entrance, Point $A$

Tests with the cable sheath grounded at $B$, the midpoint, gave similar results at the entrance $A$. Potential across the cable insulation occurred at the midpoint where the ground was located. At the far end $C$ some potential also developed by reflection phenomena. Arresters between the conductor and sheath at $A$ had no effect. Arresters at $C$ changed the measured voltages.

Many oscillograms were made during these tests under many conditions of grounding and protection. The conclusions are:

A cable with ungrounded sheath acts the same as an over head line. No potential will develop between the conductor and the cable sheath and such a cable requires no protection for itself. The traveling wave voltages in such a cable will act as though the cable were an overhead line. Thus short pieces of cable interposed in overhead lines, if the sheath is insulated will require no protection. If, however, the sheath should be grounded purposely or accidentally, the cable will require protection because high potentials will then develop between the conductor and the sheath.

The connection of a lightning arrester between the conductor and the sheath at the cable entrance with no ground is not to be recommended in general. If the cable sheath is not grounded for some distance from the entrance, potential differences between the conductor and sheath may not develop at the entrance and the maximum potential difference will probably develop where the sheath is grounded. The arrester between conductor and cable sheath at the entrance may not discharge and therefore will not exert any protective effect on the cable. It will be best to have a definite ground at the cable entrance.



Conductor voltage at $A$
Maximum = 10.5 kv

Sheath voltage at $A$
Maximum = 9.5 kv

Conductor voltage at $C$

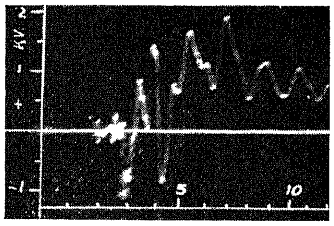


FIG. 4—VOLTAGES WITH CABLE SHEATH GROUNDED AT FAR END, POINT $C$, ONLY

**L. V. Bewley:** This paper, treating of the theory and calculations of traveling wave voltages in cables, in conjunction with an earlier paper[2] dealing with the experimental work, forms a very complete treatment of the problem. It appears, however, that the generality of the paper can be increased without undue space requirements. With that end in view the following suggestions are submitted.

1. On the first page, under $b$, it should be explicitly stated that both the *self-* and *mutual*-surge impedances are to be taken into consideration. For example, suppose that a three-phase overhead line enters three separate single-phase cables. Now if lightning strikes all three lines, the equivalent surge impedance of the overhead line is approximately

$$Z_1 = \frac{Z + 2Z'}{3} = \frac{500 + 2 \times 100}{3} = 214$$

where $Z = 500$ is the average self-surge impedance per conductor and $Z' = 100$ is the average mutual-surge impedance between pairs of conductors. Then if the self-surge impedance of each cable is 60 ohms

$$Z_2 = \frac{60}{3} = 20$$

is the equivalent surge impedance of the three cables in parallel, and the refraction factor at the line—cable junction is

$$\frac{2Z_2}{Z_1 + Z_2} = \frac{40}{234} = 0.171$$

Had the mutual-surge impedance been ignored the refraction factor would have calculated

$$\frac{2Z_2}{Z_1 + Z_2} = \frac{2 \times 60}{500 + 60} = 0.214$$

which is 25 per cent higher than the correct value.

2. The authors speak of having neglected attenuation. On the assumption of a true exponential attenuation, the formula in their Appendix I becomes

$$E_{23(n)} = AE\left[\frac{M^n - \epsilon^{-nBT}}{M - \epsilon^{-BT}}\right]\epsilon^{-\alpha T}$$

where $\alpha$ is the attenuation factor. This is easily verified.

3. The effect of waves with rounded fronts and exponential tails, such as can be represented by

$$E\,(\epsilon^{-BT} - \epsilon^{-bt})$$

follows at once, by the principle of superposition, as

$$E_{23(n)} = AE\left\{\frac{M^n - \epsilon^{-nBT}}{M - \epsilon^{-BT}} - \frac{M^n - \epsilon^{-nbT}}{M - \epsilon^{-bT}}\right\}\epsilon^{-\alpha T}$$

Since the effect of the front is small the maximum will occur at practically the same time as for the wave with an abrupt front ($b = \infty$), that is at substantially the same value of $n$ as given by the authors.

4. In these formulas, $A$ and $M$ may be put in the form

$$A = \frac{2\,(Z_2/Z_1)}{1 + (Z_2/Z_1)} \cdot \frac{2\,(Z_3/Z_2)}{1 + (Z_3/Z_2)}$$

$$M = \frac{1 - (Z_2/Z_1)}{1 + (Z_2/Z_1)} \cdot \frac{(Z_3/Z_2) - 1}{(Z_3/Z_2) + 1}$$

from which it is seen that it is the *relative* and not the *absolute* values of $Z_1$, $Z_2$ and $Z_3$ which control the transient. For example, the transient would be identical for any of the following corresponding values.

$Z_3 = 300 - 400 - 534$
$Z_2 = 267 - 300 - 400$
$Z_1 = 67 - 75 - 100$

Hereby the curves in the authors' Figs. 3 and 4 could be condensed into a single figure containing really more information, and their Fig. 5 could likewise be made more general.

**J. E. Clem:** About a year and a half ago I had occasion to analyze the voltages set up in a cable at the end of a transmission line by the impact of a traveling wave. The report made at that time, with a few modifications, is given as a discussion of the present paper.

When a traveling wave of any kind arrives at the junction between an overhead line and a cable, the voltage is initially reduced because of the lower surge impedance of the cable. With a rectangular wave, if it is long enough or the cable short enough, the voltage in the cable will build up to twice the voltage of the incident wave when the exit end of the cable is open-circuited, or to the voltage of the incident wave when the exit end of the cable connects to an overhead line. Usually the length of the traveling wave is such that these maximum voltages are not reached.

The usual traveling waves encountered in practise have a front with an approximate logarithmic increase and a tail with an approximate logarithmic decrease. The length of the front and the length of the tail may be of any value. This analysis was made to determine the maximum voltage to be expected with a damped incident wave. One of the waves proposed for insulation coordination is what is known as the 1.5–40 microsecond wave and calculations were made using this wave with, however, a slight modification (the use of a rectangular front, 0–40 microsecond, wave) which has no appreciable effect on the results of the calculations.

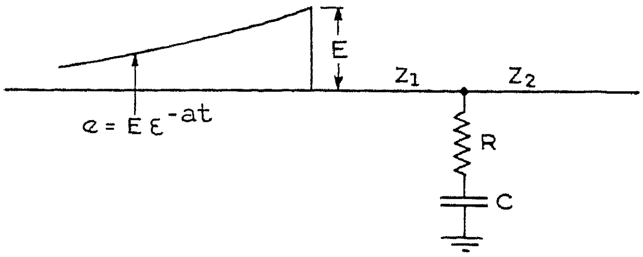


Fig. 5—Equivalent Circuit to Represent a Cable

A cable has distributed constants and for a traveling wave has appreciable series resistance and shunt conductance. On this account it is important to know whether or not calculations made on the basis of lumped constants will give results of engineering accuracy. Accordingly, two calculations were made. In the first the cable was assumed to be represented by a resistance and capacitance in series. For this calculation the total capacitance of the cable was used and the resistance was estimated on the basis of a 1.5 per cent power factor in the cable. For the calculation with distributed constants a specific cable was taken. Due to the great amount of labor required for the calculations with distributed constants it was thought that but one calculation would be sufficient.

The equations for the calculations with the lumped capacitance are developed from Fig. 5 as follows: In this figure

$E$ = initial voltage of a traveling wave
$Z_1$ = surge impedance of line on entrance side of cable
$Z_2$ = surge impedance of line at exit side of cable
$R$ = effective resistance of cable estimated from power factor
$C$ = total capacitance of cable

Since a damped wave instead of a rectangular wave is being considered, it is necessary to represent the incident wave by the following equation.

$$e = E\,\epsilon^{-at} \tag{1}$$

The operational equations for the voltage $e_0$ across the receiving circuit can be shown to be

$$e_0 = 2E\,\frac{Z_2}{Z_1+Z_2}\,\frac{R}{R_0}\,\frac{p+\dfrac{1}{RC}}{p+\dfrac{1}{R_0C}}\,\epsilon^{-at}\,\mathbf{1} \tag{2}$$

The solution of this equation is given by the usual process and is

$$e_0 = 2E\,\frac{Z_2}{Z_1+Z_2}\,\frac{1-RCa}{1-R_0Ca}\left\{\epsilon^{-at} - \frac{R_0-R}{(1-RCa)\,R_0}\,\epsilon^{-\frac{t}{R_0C}}\right\} \tag{3}$$

In order to find the maximum voltage this equation is differentiated and the differential placed equal to zero. The maximum voltage is found to be

$$\text{Max. } e_0 = 2E\,\frac{Z_2}{Z_1+Z_2}\,(1-RCa)\,M^{\frac{R_0Ca}{1-R_0Ca}} \tag{4}$$

which occurs at the time $T$ given by

$$T = -\frac{1}{a}\log M^{\frac{R_0Ca}{1-R_0Ca}} \tag{5}$$

In these equations $R_0$ and $M$ are defined as follows:

$$M = \left(1+\frac{R}{Z_1}\,\frac{Z_1+Z_2}{Z_2}\right)(1-RCa)\,R_0Ca \tag{6a}$$

$$R_0 = R + Z_1\,\frac{Z_2}{Z_1+Z_2} \tag{6b}$$

In Fig. 7 are shown two curves calculated from these equations showing the maximum voltage produced on varying lengths of cable by a 40-microsecond wave, with the cable first assumed as open at the exit end and then as connected to another overhead line.

Field tests have been made covering these two cases, the cable used having a capacitance of about 0.037 microfarads. For this value the curves give a maximum voltage on the cable for the open end condition of 1.17$E$, and 0.68$E$ when the cable joins an overhead line at the exit end. In the test referred to these ratios were found to be about 1.20 and 0.74 respectively. Although the wave used in the tests was not exactly the same as that used in the calculations it appears that not much difference in the results was found from tests with different waves.

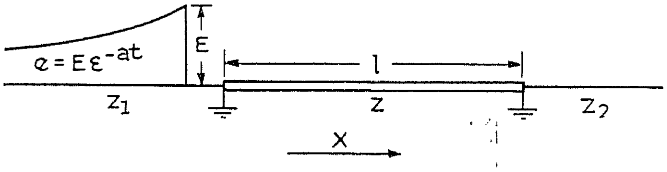


Fig. 6

The calculations for the case when the distributed constants of a cable are taken into account were made from equations developed as follows: Refer to Fig. 6 which shows a cable of length $l$ between two transmission lines. Following is an additional list of symbols.

$Z$ = surge impedance of cable
$L$ = inductance of cable per unit length
$r$ = resistance of cable per unit length
$C$ = capacitance of cable per unit length
$g$ = leakance of cable per unit length
$v$ = velocity of the impulse in the cable
$l$ = length of cable

If these cable characteristics are associated as follows:

$$\rho = \frac{r}{2L} + \frac{g}{2C} \tag{7a}$$

$$\sigma = \frac{r}{2L} + \frac{g}{2C} \tag{7b}$$

$$v = \frac{1}{\sqrt{LC}} \tag{8}$$

$$K = \frac{2Z}{Z+Z_1} \tag{9}$$

The voltage $e_c$ at any point $x$ in the cable can be shown to be

$$e_c = KE\epsilon^{-\frac{x}{v}\sqrt{(p+\rho)^2-\sigma^2}}\,\epsilon^{-at}\,\mathbf{1} \tag{10}$$

The solution of this equation is

$$e_c = KE\epsilon^{-\rho t}\left\{\epsilon^{(\rho-a)\left(t-\frac{x}{v}\right)} + \frac{x}{v}\,\frac{\sigma^2}{2}\,\frac{1}{(\rho-a)}\left(\epsilon^{(\rho-a)\left(t-\frac{x}{v}\right)}-1\right)\right.$$
$$+\frac{x^2}{v^2}\,\frac{\sigma^2}{2}\,\frac{1}{\underline{/2}}\,\frac{1}{(\rho-a)^2}\left[\epsilon^{(\rho-a)\left(t-\frac{x}{v}\right)}\right.$$
$$\left.\left. -1-(\rho-a)\left(t-\frac{x}{v}\right)\right]+\dots\right\}\mathbf{1}\frac{x}{v} \tag{11}$$

The operational equation shown in equation **(10)** is the conventional one except that the applied voltage is

$$e = E\epsilon^{-at} \qquad (1)$$

instead of the conventional rectangular wave and the fact that $K$ has been introduced to include the reflection occurring at the entrance end of the cable. The solution **(11)** of this equation is entirely new and is given in an entirely different form from that usually shown when the conventional solution for the rectangular wave is given. The solutions usually given involve more labor for the calculations and the fact that they apply to the entrance end of the cable is not at all obvious and further they are suitable only for rectangular waves. The solution here given applies to any shape of the wave, permits calculations of greater accuracy with less labor and obviously holds for the entrance end of the cable.

Inasmuch as the voltage produced in the cable by the wave depends upon reflections of the traveling wave, certain approximations were made and the equations modified to permit calculations for either end of the cable to determine the voltage produced by any number of reflections. The approximations made do not appreciably affect the accuracy over the time period of lightning surges, and the final equations are:

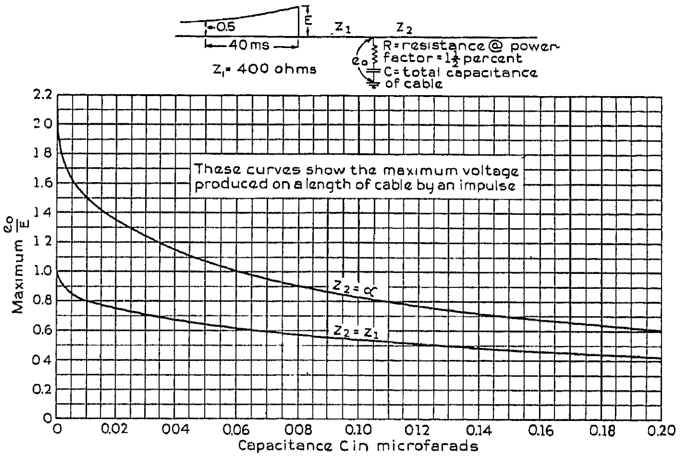


FIG. 7

$$\left.\begin{aligned} e_1 &= KE\,\epsilon^{-a2n\frac{l}{v}}\left\{1+\frac{K_1}{K_3}\right. \\ &\qquad \frac{K_3 K_4\,\epsilon^{-(\rho-a)2\frac{l}{v}}\left(1+K_3^n K_4^n\,\epsilon^{-(\rho-a)2n\frac{l}{v}}\right)}{1-K_3 K_4\,\epsilon^{-(\rho-a)2\frac{l}{v}}} \\ e_2 &= KE\frac{K_2}{K_3K_4}\,\epsilon^{-(2n-1)a\frac{l}{v}} \\ &\qquad \frac{K_3 K_4\,\epsilon^{-(\rho-a)\frac{l}{v}}\left(1-K_3^n K_4^n\,\epsilon^{-(\rho-a)2n\frac{l}{v}}\right)}{1-K_3 K_4\,\epsilon^{-(\rho-a)2n\frac{l}{v}}} \end{aligned}\right\} \qquad (12)$$

In these equations

$$K_1 = \frac{2Z_1}{Z+Z_1} \qquad K_3 = \frac{Z_1-Z}{Z_1+Z}$$

$$K_2 = \frac{2Z_2}{Z+Z_1} \qquad K_4 = \frac{Z_2-Z}{Z_2+Z} \qquad (13)$$

In Fig. 8 are given curves showing how the voltage builds up in a 1,000-ft length of cable when a 40-microsecond wave comes in from an overhead line. These calculations are based on the assumptions that the wave comes in over one conductor and in this case the inductance and capacitance involved should be from one conductor to sheath. The determination of these two factors involved a little manipulation. Published data on cable capacitance usually give two values, but it was found that these two values were not consistent with the correct geometric proportions of the cable. That is, if these two capacitances were separately calculated from the geometric proportions of the cable, a different permittivity factor would have to be used in each case. On this account calculations were remade using permittivity factor of 4. The capacitance was calculated between one conductor and sheath and the corresponding inductance determined from this quantity through the velocity relationship between inductance and capacitance. The series resistance was taken as three times the conductor resistance to allow for sheath losses and the conductance was estimated on the basis of a power factor of 10 per cent to allow for insulation losses.

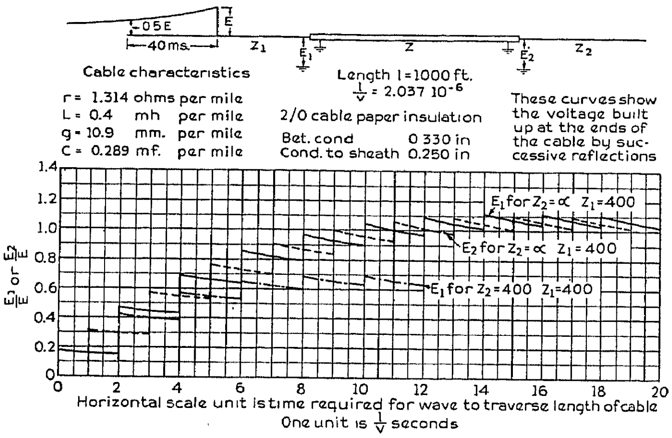


FIG. 8

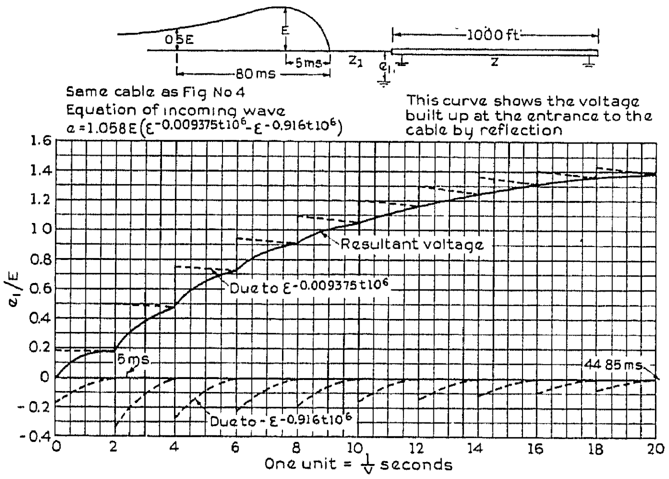


FIG. 9

As a further check, calculations were made with an applied wave closely approximating the wave used in the tests. The results are shown in Fig. 9. The maximum calculated voltage is higher than the tested maximum indicating that the more precise calculations probably indicate too high a voltage. This is no doubt due to greater losses in the cable or impulse than were assumed for the calculations.

The comparison of these calculations with previous calculations and with the test results indicates that the need of cable protection can be determined by calculations made on the basis of lumped capacitance.

If the insulation of the cable is properly coordinated with the line to which it is connected, then no protection would be needed for the cable when the voltage produced by the traveling wave in the cable is equal to or less than the voltage of the arriving wave. On this basis it appears from calculations that cable lengths from 500 to 4,000 ft might need protection, depending upon the specific conditions in each case. Longer cables very probably do not need protection. It is recommended therefore that any cable installation less than 4,000 ft in length be checked to find out whether or not protection is needed. If, on the basis that the cable at the exit end is connected to a transformer or to a very high surge impedance, the voltage appearing on the cable is greater than the voltage of the incident wave and protection may be required.

**F. H. Buller:** Mr. Beck has drawn attention in his discussion to certain points not covered in the present paper. His conclusions are those which one would naturally draw from theoretical considerations; but it is, of course, very satisfactory to learn that these conclusions are supported not by theory only but also by actual tests. The authors are in hearty accord with Mr. Beck as to the necessity of adequate grounds for arresters and cable sheaths, and the desirability of locating a definite ground at the line end of the cable sheath.

Mr. Bewley has indicated how the theory presented by the authors may readily be extended to cover special and unusual conditions, where certain factors, which in the more usual cases are of minor or negligible importance, may produce sufficient effect to affect considerably the accuracy of any calculation in which they are neglected. The four points covered in Mr. Bewley's discussion are answered in the following:

1. The authors felt that this was rather obvious and therefore did not discuss it as fully as might otherwise have been done. However, it is appreciated that this point is one which might be overlooked; and it is well, therefore, that attention has been drawn to it.

2. It has been already pointed out that in the case of short cables, which are the ones that usually need protection, the attenuation is negligible. The formula given by Mr. Bewley, however, is, of course, of value in those cases where it is desirable or necessary to take attenuation into account.

3. The authors are glad to observe that Mr. Bewley agrees with them that the effect of wave front is very slight for the types of wave under consideration. In the study of waves of a different character, however, Mr. Bewley's formula might well prove to be very useful.

4. The authors have already found that Mr. Bewley's suggestion is an extremely useful one in those cases where a large number of practical calculations must be made.

Mr. Clem has approached the problem of traveling wave voltages from an angle somewhat different from that selected by the authors; and it is very gratifying indeed to note that the results given by the two methods check satisfactorily. It is always reassuring to obtain an independent check on a mathematical theory and particularly reassuring if the procedure used in checking differs considerably from that used in the development of the original theory.

# Pulp Insulation for Telephone Cables

BY H. G. WALKER* and L. S. FORD†
Non-member Associate, A.I.E.E

***Synopsis.***—*A new type of insulation has been developed by the Bell System engineers and put into use for exchange area cables. This insulation consists of a continuous pulp or paper sleeve formed directly on the conductor by a modified paper making process. The manufacture and use of pulp-insulated wire cables involves unique changes in manufacturing equipment, materials and methods, in cable design and installation practises. The development has covered a period of some ten years and is the result of combined manufacturing, engineering, and field studies.*

* * * * *

## INTRODUCTION

OPEN wires were almost universally used for the transmission of speech in the days when telephony was young but gradually, as the need arose, the art of cable making was evolved. Today, except in the rural districts, the open wire lines have been almost entirely replaced by aerial or underground cable. The conductors in the early metal covered cables were insulated with one or two servings of cotton but in the late eighties Bell System engineers developed a spirally wrapped paper insulation so much better electrically and lower in cost that it was shortly adopted as the standard insulation for telephone cables by the growing industry. Now after some forty years of service this type of insulation is being rapidly displaced for inter-office and subscriber loop cables by a pulp insulation applied directly to the conductor by a process which brings the paper mill into the cable plant and combines the paper making and insulating operations into one process with the elimination of a number of costly intermediate steps. In addition, this process makes possible the use of a less expensive material as an insulating medium.

In order to establish a background for the logical consideration of the pulp insulation development it is desirable to cover briefly the materials, equipment and methods that have gradually been developed for the rapid application and economic use of paper ribbon insulation and indicate the limitations involved.

For many years the standard paper in this country for insulating conductors for lead-sheathed telephone cables was made from a stock composed of all old rope or old rope and a small admixture of cotton, the fibers of the rope being chiefly manila from the plant *Musa Textilis* or hemp from the plant *Cannabis Sativa*. Papers of such composition, slit into long narrow strips, were applied helically around the wire to form the insulated conductor. Experience had proved them to be highly suitable as an insulating medium, both as to structural permanency and electrical characteristics and to be sufficiently flexible and strong mechanically to admit of ready application to the conductor in manufacture and to withstand subsequent handling in service. With the increasing demand for insulating papers, however, came the urge for the finding of a suitable less expensive fiber and the year 1920 saw the adoption, for the larger sizes of paper only, of a formula composed of about 40 per cent chemical wood pulp and the remainder rope stock. This wood fiber is of the spruce or other coniferous tree species prepared by the sulfate or "Kraft" process. It is required to have a high cellulose content and to be as free from water soluble salts as the best manufacturing practise will permit. Extensive tests have demonstrated that it compares favorably in stability and permanence with the well-established manila fiber. In the case of pulp insulated cable which is discussed in this paper the raw material used is 100 per cent of this wood fiber.

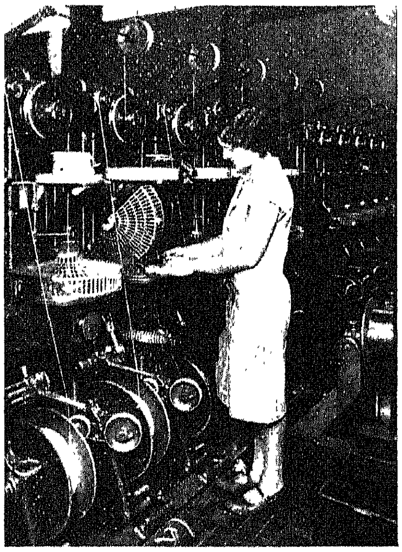


FIG. 1—RIBBON PAPER INSULATORS

The present day ribbon paper insulating machine as developed by the Western Electric Company is essentially a rotatable hollow tapered spindle centrally mounted on and integral with a light weight disk about 15 inches in diameter. (Fig. 1.) The wire to be insulated passes through the spindle over a capstan and to the take-up spool. The insulating paper wound into a pad or disk is slipped over the spindle and supported by the metal disk. This whole assembly is arranged to rotate rapidly around the wire and feed the paper ribbon from the periphery of the pad through guides so as to form a continuous spiral wrapping around the wire which is advanced at a definite speed by the capstan. The speed of rotation of the spindle is approximately 3,300 r.p.m. and the wire advances from 175 to 200 feet per minute depending on the length of wrap.

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*Western Electric Co., Inc., Kearny, N. J.

†Bell Telephone Laboratories, Inc.

*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

From a process standpoint manila paper was selected originally because of its strength and elasticity, and in the development of equipment to serve it, full advantage was taken of these two characteristics, particularly for the insulation of the finer gages of wire. This fact tended to handicap the adaptation of cheaper papers to this purpose when the changing conditions in the paper industry made such a step desirable, since the readily available substitutes were somewhat inferior in these two respects. Studies were undertaken to modify the equipment for serving ribbon paper with the idea of adapting it for handling this paper, but with only indifferent success. The mixing of varying amounts of wood pulp with manila stock proved to be a successful solution in the case of heavier papers, but in the thinner ones the results were not satisfactory, and progress in this direction was at a standstill.

## THE DEVELOPMENT OF PULP INSULATED WIRE

In line with the generally recognized need for a radical change in the insulation situation, some work was initiated in 1921 with the idea of determining the possibilities of producing a continuous homogeneous paper covering directly on the wire, and a scheme was worked out, which after some preliminary experiments, gave sufficient promise of success to suggest the desirability of going ahead with the development of the idea and the mechanism to carry it out.

A crude paper machine of the cylinder type was built and with this the feasibility of the basic idea was demonstrated. Dryers were next improvised and sufficient wire was insulated to give a few short test cables. These, of course, were made from carefully selected insulation for only a small part of the wire made was usable. The test results on these cables were sufficiently interesting to warrant proceeding further with the project. After considerable study and experiment it was decided to build a ten-wire machine adaptable to future expansion if the anticipated results were realized. This 10-wire machine was started up with very indifferent success in January, 1924. During that year an operating technique was gradually developed and numerous improvements made in the equipment. In 1925, a great many test cables were made and several were installed for use in the telephone plant. Experience with the 10-wire operation and product finally became so satisfactory that it was decided to expand the machine to a 50-wire capacity and put it on as near a commercial basis as possible, in order that its operation, product, and economics might be studied to better advantage. Accordingly, the necessary auxiliary equipment was purchased and installed and the machine converted to a 50-wire basis.

The installation was completed early in 1928 and the machine put in experimental operation about March of that year. As rapidly as possible crews were broken in and late that summer the machine was placed on a regular operating basis with three complete crews on a twenty-four hour day and six-day week. It continued to operate on this basis until 1931, when ten more wires were added. This product was cabled into 26 and 24 A.W.G. cables on standard cabling equipment with no major difficulties and installed in commercial telephone plant by the operating companies. No serious operating trouble has developed in any of this cable.

The pulp insulated wire capacity now at the Hawthorne and Kearny plant is approximately 225 million conductor feet per week and all 24 and 26 A.W.G. exchange area cables are being manufactured from pulp insulated wire.

## PROCESS

Essentially the process consists in forming simultaneously on a modified cylinder paper machine 60 narrow continuous sheets of paper with a single strand of wire enclosed in each sheet, pressing the excess moisture from the sheets, turning them down so as to form a uniform cylindrical coating of wet pulp around the wire and then driving the water from this coating by drying at a high temperature. (Fig. 2.)

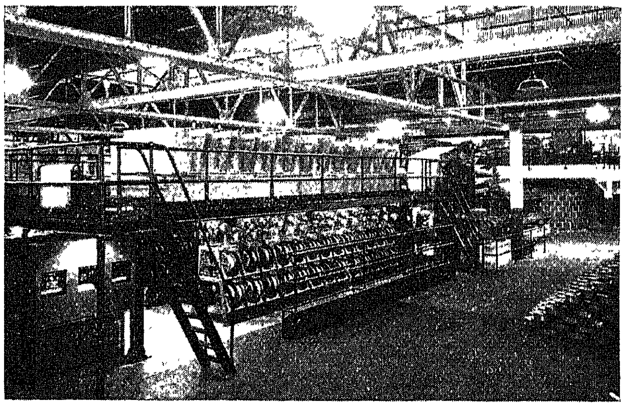

FIG. 2—GENERAL VIEW OF PULP INSULATING EQUIPMENT

Take-up and dryer in left foreground, polishers and wet machine in right center. Wire supply and pulp preparation equipment in right background

The insulating material is given practically the same treatment in a beater as it would receive in paper making, but without the addition of sizing or loading. The beaten pulp is stored in a large tank from which it is pumped to a mix box for dilution with water before passing to the screen where coarse particles and lumps are removed. (Fig. 3.)

For the next operation a modified paper machine of the cylinder type is used. The mixture of pulp and water is fed into the cylinder vat by gravity from the screen. The cylinder mold itself is divided into 60 narrow, uniform sections by dams or deckles on the surface of the wire cloth covering. The bare conductors coming to the machine are guided so that one conductor passes around the mold in each of the sections. As the mold is rotated in the water suspension of pulp in the vat, a narrow continuous sheet of paper with a conductor embedded in it is formed in each section by the simple paper making process of straining the fibers from the suspension as the water flows through the fine wire cloth covering the mold, under the slight head maintained outside the mold. These sheets are transferred from the mold to a woolen felt by the pressure of a couch roll and carried by it through two presses which take out a considerable part of the water and leave the material in shape to be turned down to the final form. This is done by passing the conductors embedded in the narrow sheets through individual polishers which turn the wet sheet down into a uniform covering of a size determined to a large extent by the amount of pulp deposited in the sheet. These polishers are simply rapidly rotating heads carrying three specially shaped blades so arranged that one blade deflects the traveling wire and sheet from a straight line against the other two with a pressure controlled by the tension on the wire.

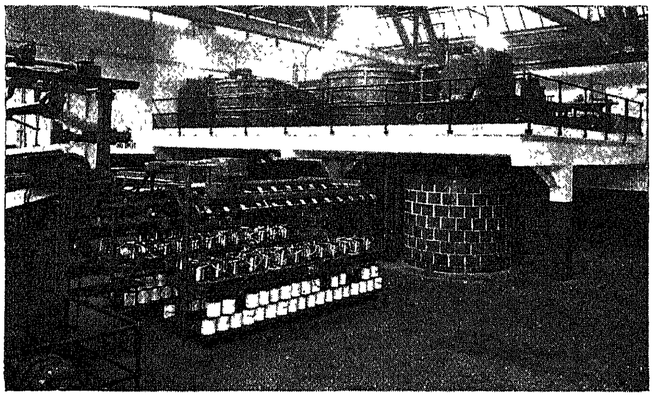

FIG. 3—WIRE SUPPLY AND PULP PREPARATION EQUIPMENT

The wet cylindrical insulation is then dried to about a 9 per cent moisture content by a single passage through a horizontal electric furnace 26 feet long the wet end of which is maintained at a temperature of about 1,500 deg. fahr. and the dry or tempering end at something under 800 deg. fahr. The wires are carried through the drier by a rotary pulling mechanism designed to minimize the crushing or flattening of the dried insulation. This device delivers the finished product to the take-ups for spooling. The machine is operated at about 130 feet per minute.

Considerable amounts of water are used in the process, for in this, as in all paper making processes, water acts not only as a carrier for the fibers, but it forms some sort of a loose chemical or mechanical combination with them in the beater which is one of the principal factors in determining the final characteristics of the material. The approximate fiber concentrations at the various steps of manufacture are as follows:

| | Per cent |
|---|---|
| Beater | 3.5-4 |
| Storage | 1.3 |
| Screen | 0.07 |
| Cylinder vat | 0.05 |
| Polishers | 28 |
| Completed insulation | 91 |
| Finished cable | 100 |

## SOME PROBLEMS INVOLVED

In theory the whole process is remarkably simple, but from the practical standpoint, many intricate problems had to be solved before satisfactory operation was possible. In some cases it was rather difficult to segregate the problems for study as there were so many variables involved. Gradually, however, these details have been cleared up and today operation is quite satisfactory. A brief survey of some of the more important problems and their solutions may be of interest.

*Continuous Operation.* It is quite essential, from an economic standpoint, that the machine should operate continuously. The fact that the supply spools carry only a limited amount of wire necessitated the working out of a dependable means for shifting from an empty to a full spool without a shutdown or break in conductor or insulation. This is accomplished by taking the wire off over the head of a spool by means of a flyer and brazing the inner end of the wire on one spool to the outer end of the next, Fig. 4. Again in spooling the finished material at the dry end, the wire must be transferred from a full spool to an empty spool without interfering with the operation of the machine, Fig. 5. This has been taken care of very simply by providing two spool positions for each wire with a simple manual means of shifting from one to the other.

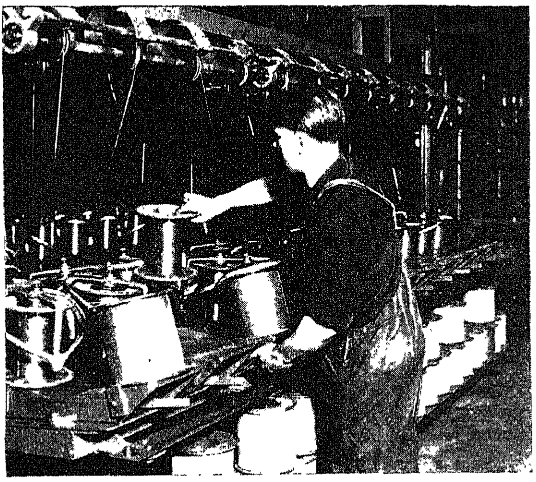

FIG. 4—CHANGING SPOOLS AT SUPPLY END

*Broken Wires.* In spite of all the care that can be exercised, wires break at times and as a matter of economy, methods of restringing the broken wires with the machine in operation had to be worked out as shown in Fig. 6. Continuous six-day week operation is now possible without shutdowns except for the midweek clean-up.

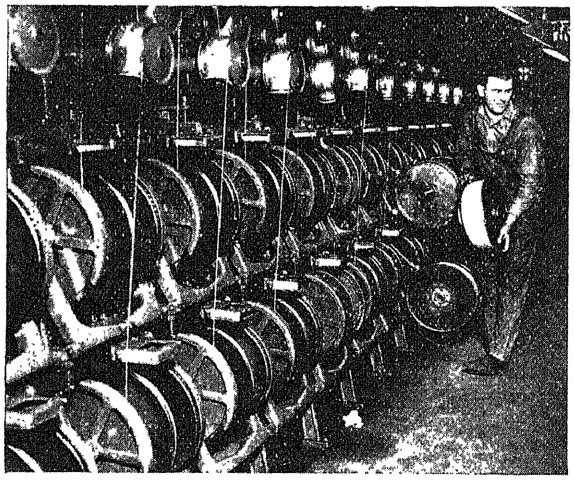

FIG. 5—CHANGING SPOOLS AT TAKE-UP

*Wire Cleaning.* The supply wire comes to the machine on spools. It is spooled on the wire drawing machine and annealed on the spool. The surface of this wire, annealed with the drawing compound on it, seems to act somewhat as a repellant to wet pulp and causes a ragged, broken insulation. This is probably due to a surface tension effect. This action caused considerable trouble in the early stages of the work as the blame was placed on polishers, pulp, felts, or anything but the wire surface. Finally it became apparent that the surface condition of the wire was a large factor and the trouble was eliminated by passing all the bare wires through an a-c. electrolytic cleaner between the supply stand and the wet machine.

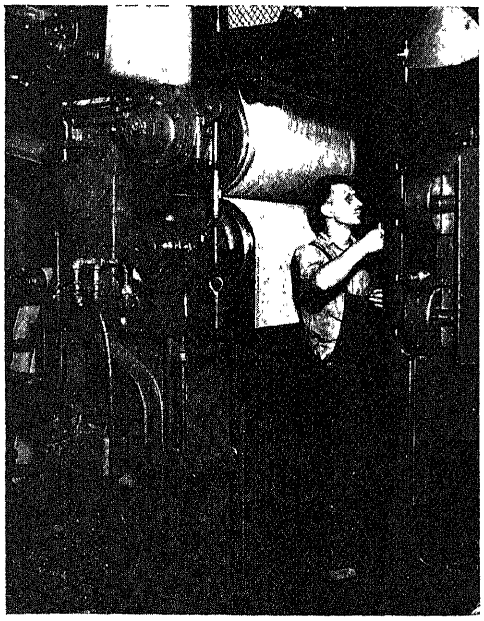

FIG. 6—STRINGING IN A WIRE AT POLISHERS

*Tensions.* Fine gage copper wire is soft and easily stretched, pulp insulation in the wet form possesses very little strength, and in the dry form its elongation is much lower than spirally wrapped ribbon insulation, hence it is necessary at every step in the process to maintain minimum tensions in order that the wire may not be stretched and the insulation opened. Devices have been developed that are quite efficient in holding tensions within the safe range.

*Pick-Up.* In the early operating stages the pick-up from the mold was at times ragged and uneven and the sheet formation not all that could be desired. It was found that these conditions could be materially improved by the addition of a very small amount of soap to the pulp suspension immediately before it reaches the machine.

*Polishing.* In connection with the operation of polishing the sheet down to a circular insulation, it has been found that a water content of approximately 72 per cent is preferable to a dryer or wetter sheet as it seems to felt down and form a more homogeneous insulation. The polisher itself has required a considerable amount of development work to insure a continuous uniform product and avoid stripping when a lump or break in the sheet occurs.

*Drying.* Several methods of drying pulp insulation were given a thorough trial but a completely satisfactory drier did not prove a simple thing to find. Finally, however, it was discovered that very rapid drying caused less shrinkage than slower drying, and so resulted in a less dense insulation. As a low density insulation is very desirable electrically, this was the deciding factor in adopting high temperature radiant heat drying and experience has amply justified the decision.

*Operation.* The development of operating technique and methods offered some difficulties as the process is neither wholly paper making nor wire handling. Preliminary methods were worked out by engineers on the machine. Then regular operators were recruited for the most part from the operating organization and broken in to the work. Most of them had never seen a paper machine before but they became very efficient in a surprisingly short time and there have been no prejudices acquired on regular paper machines to overcome.

*Making Narrow Ribbons.* The making of narrow uniform ribbons has given considerable trouble. The most satisfactory solution of this problem to date is the use of deckles or dams painted on the mold mechanically at spaced intervals. Apparently very good life can be expected from such a mold.

*Defective Wire.* It is necessary to mark defects in the completed wire by placing a white tag in the winding in order that repairs may be made by the twister operators, as there is no opportunity to make them at the pulp machine take-ups. Short breaks in the insulation were often passed unnoticed by the operators so a bare wire detector was put in which sounds an alarm, indicates the spool position by a light and records the break by number on a position counter and on a master counter. If any one spool shows excessive defects it is rejected.

## GENERAL PHYSICAL CHARACTERISTICS

Pulp insulation is a new product and has certain inherent characteristics. These characteristics may be modified somewhat by choice of materials and methods of manufacture but they can not be entirely controlled. A brief survey of these characteristics may be of interest to illustrate the possibilities and limitations of the product. This survey covers only 24 and 26 A.W.G. wire as these are the sizes which have been run almost exclusively to date. It should be noted, however, that wires ranging in size from 19 to 28 A.W.G. have been covered successfully.

Some of the physical characteristics of the insulation are shown below in tabular form giving the possible range of values obtainable. They are controlled by the beating of the pulp, the amount of pulp fed to the machine, the dryness of the sheet in the polishers, and the speed of drying.

| | |
|---|---|
| Diameter of insulated wire—inches........ | 0.030 to 0.050 for 24 A.W.G.<br>0.026 to 0.040 for 26 A.W.G. |
| Weight of dry pulp—grams per foot....... | 0.045 to 0.12 for 24 A.W.G.<br>0.040 to 0.095 for 26 A.W.G. |
| Density—ratio of fiber to total volume.... | 35% to 55%—independent of gage |

The tensile strength and flexibility of the insulation can be varied through rather wide limits by different treatments during manufacture. The elongation is quite comparable to that of ordinary paper and is not susceptible of much variation. The insulation is made sufficiently strong and flexible to withstand the various operations incident to cable fabrication and subsequent handling yet not so tough that it cannot be readily removed from the wire at the point of splicing.

The surface of the insulation has a rather rough blotting paper appearance, though some variation is possible by changes in the beating. The cross-section is circular with the conductor in the center in the ideal case, but because of limitations imposed by practical operating considerations there is a tendency toward some eccentricity and flattening of the insulation.

## PULP INSULATED CABLES

*Design.* The smallest wires now used in commercial telephone cables are 24 and 26 A.W.G. and it has been found that pulp is particularly suitable for insulating such fine wires. Here it is in direct competition with non-wood content strip paper that has been giving satisfactory quality performance. To displace the old standard, pulp must meet this competition and give a greater return for the money invested.

Telephone cable circuits are normally subjected to only a low dielectric stress which permits their being placed in close proximity to one another and the primary requirement of the insulation is that it be distributed in a thin layer of uniform application, with the wire well centered so that each conductor when packed into a cable is completely insulated from its neighbors throughout its length. The mean radial thickness of the pulp insulation for the 26 A.W.G. wire which is in common use is less than 0.01 inch and for 24 A.W.G. which is the next larger size of wire usually used for telephone cables this value is about 0.011 inch. The pulp is prepared and applied to the conductor in such a manner that the fibers pack together to form a cover with sufficient strength and elasticity to withstand the handling the insulated wire must receive and yet be as light as possible in weight per unit volume in order to obtain the best electrical characteristics.

At the time this development was started 24 A.W.G. wire was the finest regularly used and the earlier pulp cables were confined to this gage. Pulp insulated wire is structurally more like textile insulated wire than air-spaced paper ribbon insulated wire. The insulation is firm with no appreciable air gap between it and the wire, and bundles of wires nestle together differently when grouped into a given space. Furthermore, it was found that when pairs of conductors were stranded together in the usual manner of concentric layers each reversed in direction, the unit thus formed was considerably less flexible than the standard construction. This is apparently caused by the greater frictional resistance between layers sliding over each other as the cable is bent, thus causing sharp kinks for even moderate bends. While this feature is less pronounced for small cables, it is, of course, objectionable and an improvement in the handling qualities is effected by stranding several layers in the same direction rather than employing the single reverse layer construction.

For the large size cable, a design whereby the pairs are first grouped into units of fifty-one or one hundred and one, all the pairs in these units being stranded in the same direction and the units then stranded together into a cable, gives a construction which seems to offer the most satisfactory arrangement. Thus, for example, a 1,212-pair cable is made up of 12 units of 101 pairs each, arranged with four units in the center and eight in a surrounding layer, and an 1,818-pair cable is laid up with two units in the center surrounded by six units in the first layer and ten units in the second layer. Fig. 7 shows a short section of 1,818-pair 26 A.W.G. cable with the units separated. One might expect these rather large units would not group themselves together into a circular shape without poor utilization of the space they occupy but it has been found that by properly constructing the individual units and by suitable arrangement of the cable layup, a cross-section is obtained with the groups keystoning together nicely and presenting no noticeable voids.

The cable core must also have a certain firmness or density to give the best support to the sheath and insure satisfactory handling as the cables are being installed. With ribbon paper insulation the ratio of the amount of insulation to the non-copper space in a cable was found to be a fairly good criterion of the firmness required. With the fundamentally different physical characteristics of the pulp insulated wire this relationship was altered and experimental trials were therefore necessary to determine the approximate size of pulp insulated wire most suitable for the space it was to occupy in cable form. There is some latitude here in the distribution of a given amount of fiber but taking into account both the mechanical and electrical requirements, the diameter for the insulated conductor finally selected as the most satisfactory for the series of standard cables of 24 A.W.G. was 0.041 inch and for 26 A.W.G., 0.033 inch; and the aim in manufacture is to produce an insulation as uniformly close to these dimensions as possible. These diameters are measured by a volume displacement method. Short samples, as representative as possible of the wire under consideration, are inserted for a given distance into a small bore tube of mercury and the displacement noted. The gage is calibrated so that mean diameters are read directly on the scale.

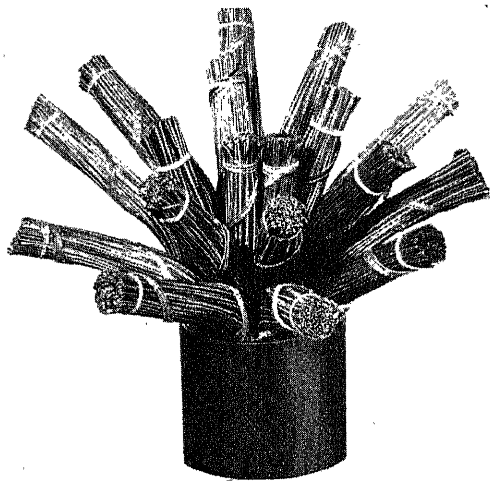

FIG. 7—SECTION OF 1,818-PAIR 26 A.W.G. CABLE SHOWING UNITS SEPARATED

The above specific sizes of pulp insulated conductors apply only to cables designed for a particular set of characteristics. As in the case of ribbon paper cables, the amount of insulation for a given gage of conductor may be varied within reasonable limits, so as to produce cables of other characteristics.

*Electrical Characteristics.* It was reasoned that pulp insulated cables would probably be inherently higher in mutual capacitance than similar sizes of paper ribbon cables because, considering the insulated wire itself, in the case of helically applied strip insulation the volume of air beneath the paper is about equal to the volume of the paper itself, while for pulp insulation there is very little air space between the insulation and the wire. This fundamental difference could be somewhat compensated for, however, by the introduction of more air into the spaces between the fibers of the pulp insulating medium than is found in the paper ribbon itself, but it was not expected that it would entirely neutralize the effect of lack of air space next to the wire. It was appreciated, however, that the aim should be to get as low density insulation as possible still consistent with obtaining a continuous, flexible, and strong covering on the wire and emphasis was placed on this phase from the start of the development.

The very first experimental cables manufactured compared favorably in mutual capacitance with corresponding sizes of strip paper cables. The wire was insulated in a manner resulting in an apparently well centered, round insulation and the covering was low in weight of fiber per unit volume. The insulation after being formed around the wire was quickly dried in a hot tube resulting in less shrinkage and tightening down around the wire while the moisture was being driven out than if slowly dried. The insulation was unsatisfactory, however, from a continuity and tensile strength standpoint and could not be considered as suitable for commercial cable.

Special effort was then directed towards producing an insulation better mechanically, with the result that the early commercial cables were satisfactory in this regard but were from 20 to 25 per cent higher in mutual capacitance than the standard ribbon paper cable. This impairment in transmission efficiency was considered prohibitive for cables to be used for interoffice trunks and was definitely objectionable for any class of service. However, the indicated savings in cable first cost warranted continuing the development, and over a period of years marked progress has been made in reducing this excess of capacitance and yet retaining an insulation sufficiently strong and flexible to handle with reasonable satisfaction in the fabricating of the cable and installing it in the plant. Fig. 8 shows graphically the progress that has been made in reducing the mutual

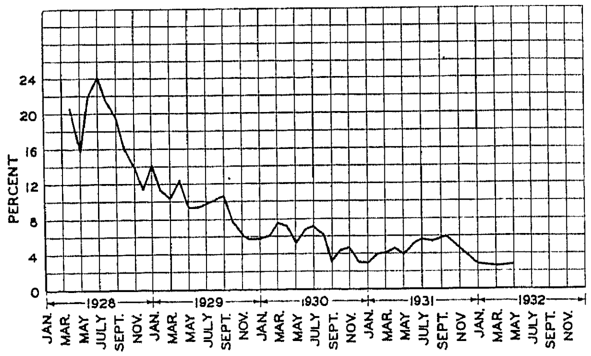

FIG. 8—CURVE SHOWING IMPROVEMENT IN MUTUAL CAPACITANCE SINCE EARLY 1928

Per cent by which capacitance of No. 24 A.W.G. pulp insulated cables exceeds that of ribbon capacitance of 24 A.W.G. cable since early in 1928. Although a substantial improvement has been made in lowering the mutual capacitance to within less than 4 per cent of the corresponding ribbon paper cable, a further reduction would have considerable value, warranting more effort in that direction. For 26 A.W.G. cable the excess in capacitance is even less than for 24 A.W.G., and furthermore, it is not so objectionable from a transmission standpoint as in the case of the larger gage.

The principal factors which have brought about this reduction in capacitance are improvements in the treatment of the pulp itself, refinements in machinery operation to permit the use of a lower density covering on the wire, the more rapid drying out of the moisture from the pulp resulting in less shrinkage of the insulation on the conductors and the producing of more nearly round and better centered insulation. Of these factors perhaps the one having the greatest effect on lowering the mutual capacitance was that of improving the out-of-roundness of the insulated conductors. In studying this phase of the problem, advantage was taken of the effect of flatness of the insulation on the component parts which make up the mutual capacitance. The mutual capacitance of a pair of wires is composed of the direct capacitance between the two wires augmented by a series arrangement of two other direct capacitances, one from each of the two wires to the grounded group consisting of all other wires and sheath. As two wires with oval shape insulation are twisted, there is a decided tendency for two flat sides to stay together resulting in the average separation of wire and mate being less than where circular sections are involved. To determine accurately the degree of out-of-roundness representing the average condition throughout a length of cable by mechanical means is next to impossible, whereas the direct capacitance between wire and mate automatically integrates this condition. Measurements therefore are made of the component direct capacitances and their ratio used as a sensitive indicator of the effect of flatness of the insulation on the mutual capacitance. By using the ratio of capacitances the cable length error is eliminated and accurate determination can readily be made on short lengths of cable.

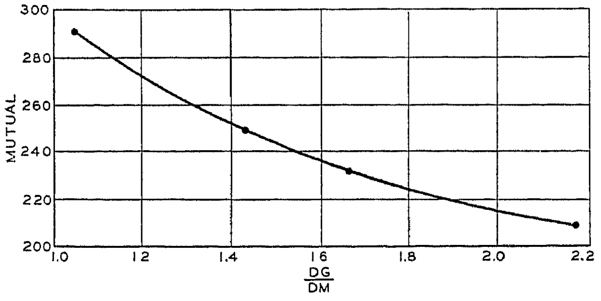

FIG. 9—CURVE SHOWING MUTUAL CAPACITANCE VERSUS DIRECT CAPACITANCE TO GROUND DIVIDED BY DIRECT CAPACITANCE TO MATE

As illustrative of the above relation there are given in the following table and curve, (Fig. 9) data which were obtained on four short lengths of pulp insulated cables which so far as was known differed only as regards the lack of symmetry of the insulation.

Mutual Capacitance *vs.* $\frac{\text{Direct Capacitance to Ground}}{\text{Direct Capacitance to Mate}}$

Average value in $\mu\mu$f.

| Sample | Mut. | $D_M$ | $D_G$ | $D_G/D_M$ |
|---|---|---|---|---|
| 1 | 292 | 187 | 201 | 1 07 |
| 2 | 250 | 144 | 207 | 1.42 |
| 3 | 233 | 126 | 209 | 1.66 |
| 4 | 206 | 101 | 221 | 2.19 |

The alternating-current mutual conductance follows the trend of the capacitance, resulting in the ratio of conductance to capacitance at a frequency of 900 cycles per second being somewhat higher than the standard ribbon paper cable, but not of a magnitude such as to introduce any serious transmission loss for these fine gage circuits. The direct current insulation resistance is of the same order as that of strip paper cables.

The dielectric strength of the insulation is ample, being somewhat higher on the average than that of similar strip paper cables. A rather extensive series of mechanical tests comparing pulp and ribbon types of insulated cable under controlled conditions simulating those met with in actual installation, showed that the pulp insulated cables remained superior to the ribbon cables as regards dielectric strength but that under extreme loads they would not withstand quite as much stretch as the ribbon insulated cable without mechanical damage to the insulation.

*Installation Features.* No new features are involved in installing pulp insulated cable except in the splicing of the conductors after the lengths as supplied from the factory have been placed in position in the plant. This operation, however, is a considerable factor in the total time of the installation procedure because in a not unusual run of a mile of an 1,818-pair cable, there may be as many as 40,000 joints to be made involving the stripping of twice that number of ends of insulated wire preparatory to joining the copper conductors.

Immediately upon removing the lead sheath from the ends of the cables thus exposing the dry insulation to the atmosphere, absorption of moisture rapidly takes place. It is customary therefore to boil out the ends of cable with paraffin wax before starting the splicing operation. With strip insulation this wax also aids in preventing the insulation from unfurling. It was found that even the most flexible pulp insulation so far produced, when impregnated with unmodified paraffin would not withstand satisfactorily the handling incident to splicing at low temperatures. A softer and more lubricating type of compound is required and a suitable combination has been found by adding paraffin oil to the groups keystoning together nicely and presenting no noticeable voids.

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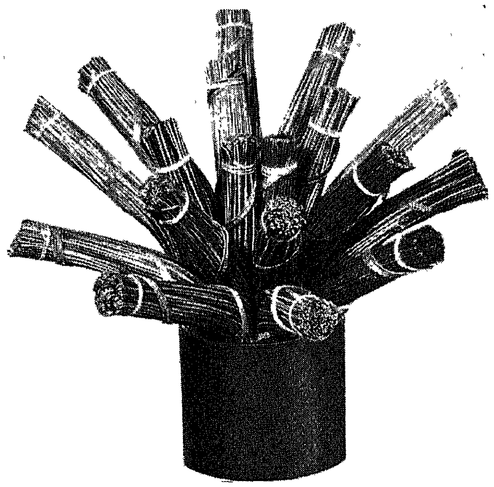

Fig. 7—Section of 1,818-Pair 26 A.W.G. Cable Showing Units Separated

The above specific sizes of pulp insulated conductors apply only to cables designed for a particular set of characteristics. As in the case of ribbon paper cables, the amount of insulation for a given gage of conductor may be varied within reasonable limits, so as to produce cables of other characteristics.

*Electrical Characteristics.* It was reasoned that pulp insulated cables would probably be inherently higher in mutual capacitance than similar sizes of paper ribbon cables because, considering the insulated wire itself, in the case of helically applied strip insulation the volume of air beneath the paper is about equal to the volume of the paper itself, while for pulp insulation there is very little air space between the insulation and the wire. This fundamental difference could be somewhat compensated for, however, by the introduction of more air into the spaces between the fibers of the pulp insulating medium than is found in the paper ribbon itself, but it was not expected that it would entirely neutralize the effect of lack of air space next to the wire. It was appreciated, however, that the aim should be to get as low density insulation as possible still consistent with obtaining a continuous, flexible, and strong covering on the wire and emphasis was placed on this phase from the start of the development.

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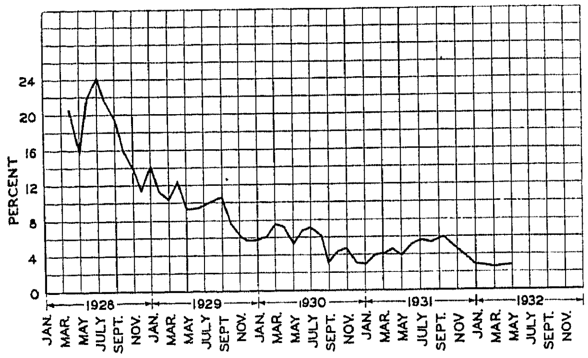

Fig. 8—Curve Showing Improvement in Mutual Capacitance Since Early 1928

Per cent by which capacitance of No. 24 A.W.G. pulp insulated cables exceeds that of ribbon capacitance of 24 A.W.G. cable since early in 1928. Although a substantial improvement has been made in lowering the mutual capacitance to within less than 4 per cent of the corresponding ribbon paper cable, a further reduction would have considerable value, warranting more effort in that direction. For 26 A.W.G. cable the excess in capacitance is even less than for 24 A.W.G., and furthermore, it is not so objectionable from a transmission standpoint as in the case of the larger gage.

The principal factors which have brought about this reduction in capacitance are improvements in the treatment of the pulp itself, refinements in machinery operation to permit the use of a lower density covering on the wire, the more rapid drying out of the moisture from the pulp resulting in less shrinkage of the insulation on the conductors and the producing of more nearly round and better centered insulation. Of these factors perhaps the one having the greatest effect on lowering the mutual capacitance was that of improving the out-of-roundness of the insulated conductors. In studying this phase of the problem, advantage was taken of the effect of flatness of the insulation on the component parts which make up the mutual capacitance. The mutual capacitance of a pair of wires is composed of the direct capacitance between the two wires augmented by a series arrangement of two other direct capacitances, one from each of the two wires to the grounded group consisting of all other wires and sheath. As two wires with oval shape insulation are twisted, there is a decided tendency for two flat sides to stay together resulting in the average separation of wire and mate being less than where circular sections are involved. To determine accurately the degree of out-of-roundness representing the average condition throughout a length of cable by mechanical means is next to impossible, whereas the direct capacitance between wire and mate automatically integrates this condition. Measurements therefore are made of the component direct capacitances and their ratio used as a sensitive indicator of the effect of flatness of the insulation on the mutual capacitance. By using the ratio of capacitances the cable length error is eliminated and accurate determination can readily be made on short lengths of cable.

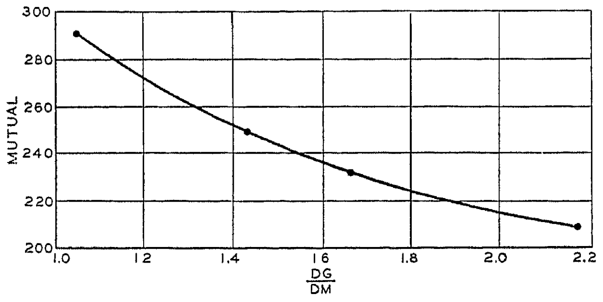

Fig. 9—Curve Showing Mutual Capacitance Versus Direct Capacitance to Ground Divided by Direct Capacitance to Mate

As illustrative of the above relation there are given in the following table and curve, (Fig. 9) data which were obtained on four short lengths of pulp insulated cables which so far as was known differed only as regards the lack of symmetry of the insulation.

Mutual Capacitance *vs.* $\frac{\text{Direct Capacitance to Ground}}{\text{Direct Capacitance to Mate}}$

Average value in $\mu\mu f$.

| Sample | Mut. | $D_M$ | $D_G$ | $D_G/D_M$ |
|---|---|---|---|---|
| 1 | 292 | 187 | 201 | 1.07 |
| 2 | 250 | 144 | 207 | 1.42 |
| 3 | 233 | 126 | 209 | 1.66 |
| 4 | 206 | 101 | 221 | 2.19 |

The alternating-current mutual conductance follows the trend of the capacitance, resulting in the ratio of conductance to capacitance at a frequency of 900 cycles per second being somewhat higher than the standard ribbon paper cable, but not of a magnitude such as to introduce any serious transmission loss for these fine gage circuits. The direct current insulation resistance is of the same order as that of strip paper cables.

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Immediately upon removing the lead sheath from the ends of the cables thus exposing the dry insulation to the atmosphere, absorption of moisture rapidly takes place. It is customary therefore to boil out the ends of cable with paraffin wax before starting the splicing operation. With strip insulation this wax also aids in preventing the insulation from unfurling. It was found that even the most flexible pulp insulation so far produced, when impregnated with unmodified paraffin would not withstand satisfactorily the handling incident to splicing at low temperatures. A softer and more lubricating type of compound is required and a suitable combination has been found by adding paraffin oil to the paraffin wax. Different proportions of oil and wax are used depending upon the temperature at the time of installation and the compounding is done at the point of splicing. At an atmospheric temperature of about 75 deg. fahr. no oil is required and below 10 deg. fahr. about half oil and half wax makes a suitable compound with proportionate amounts of oil for intermediate temperatures.

In starting to make a splice, the insulated conductors are brought together in proper position, given a sharp crossover, the wires cut off so as to give several inches of free end, the insulation broken at the crossover and then stripped off the ends. Thus the ideal insulation is one which when waxed, can readily be parted at the crossover and when broken will slip freely along the wire, yet will withstand considerable bending and folding at other places in the splice without breaking. Pulp insulation tends to cling to the conductor somewhat more than a paper tube of strip insulation and although there is considerable variation in this characteristic in the product as now manufactured, it is sufficiently under control so that with a small amount of experience a splicer applying his usual technique is able to handle even 26 A.W.G. wire with little breaking of the conductors.

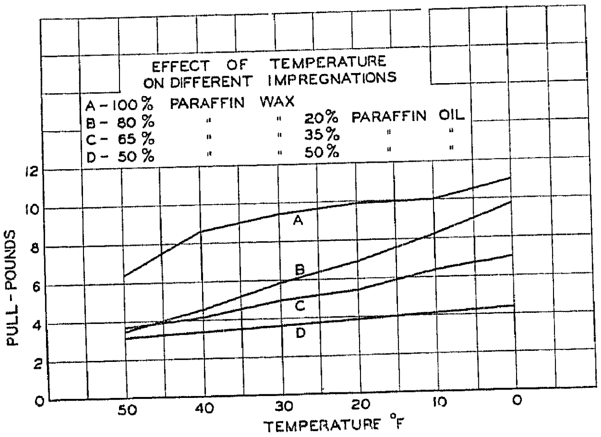

Fig. 10—Curve Showing Effect of Temperature on Pull Required to Strip Insulation Impregnated with Various Wax and Oil Mixtures

Fig. 10 shows the stripping characteristics of typical pulp insulation on 24 A.W.G. conductors impregnated with compounds of different proportions of paraffin wax and oil. The pull required to strip the insulation from a few inches of wire is plotted against atmospheric temperature and shows the benefit of the higher percentage of oil particularly at the lower temperatures. There is, of course, with pulp no raveling of the insulation and the cotton sleeves which are used to insulate the joint, slip over the ends of the wires rather more readily than for the spirally applied paper. Thus the overall time required for joining a given number of pairs is practically the same for the two types of insulation.

An unbleached pulp is used and the natural brownish color of the Kraft stock results in less sharp color distinction for the different groupings of pairs than where ribbon insulation is used. However, by simplifying the color code so as to require only red, blue, and green, besides the natural color, sufficient contrast in the shades is obtained so that there is no difficulty in distinguishing colors in the splicing operation.

## Possible Applications

This work was undertaken primarily to develop an insulation for use in exchange area cables and efforts have been confined largely to this phase of the study. It is possible to vary the characteristics widely by changes in the raw materials, process, and subsequent treatment; other fields of use are being considered.

Pulp insulation is being used as sleeving for lead-in wires in some apparatus at the present time. For this purpose the insulation is made on 19 A.W.G. wire, stripped from the wire and cut in short lengths. It has proven quite superior to the old paper sleeves rolled by hand over mandrels.

Preliminary tests have indicated that there may be a field for the use of this type of insulation with certain modifications for switchboard wiring, terminating cables, and some kinds of coils.

## Economies

Preliminary cost figures indicated that this process offered the possibility of a considerable saving over the ribbon process. These predictions have been verified by actual machine operation extending over a period of more than three years. The savings are made possible by the low cost of Kraft pulp as compared with manila paper and by the elimination of the intermediate paper making, paper slitting, and handling operations.

## Conclusions

A new type of insulated wire which is considerably cheaper than paper ribbon insulation has been developed. The insulation is formed from paper pulp directly on the conductor by a special type of paper making equipment. This equipment is not critical to the kind of pulp used but for the purposes of durability, strength and economy a Kraft wood pulp has been used in telephone cables. The process has progressed through the development stage and is now in continuous operation in the commercial production of all the principal exchange area cables of 24 and 26 A.W.G. conductors used in the Bell system. Thousands of miles of lead-encased pulp-insulated cables, ranging in size from the smallest consisting of 11 pairs to the largest consisting of 1,818 pairs, are now giving satisfactory service and because of the substantial economies which the construction promises for the finer wire cables, attention is being directed toward its possible application to larger gage cable conductors and to its use as an insulating medium for other electrical circuits.

## Discussion

**W. A. Del Mar:** Has this insulation flexibility when applied in heavy layers such as 50 mils or over? The paper closes with a suggestion of new applications. Have any of these materialized in the interim since the writing of the paper?

**Robert J. Wiseman:** What is the nature of the wood pulp that the authors are using, that is, is it spruce fiber? Also, as a result of this method of insulating the conductors and assembling, we should get a more firm cable than the usual method of making telephone cable, namely, a certain degree of softness of the cable. At the present time, antimonial lead is used for the lead sheaths of the telephone cables. Have the Western Electric considered using pure lead for these cables for the cases where the cable is drawn into duct? Of course, with aerial cable, they would continue to use antimonial lead.

**L. S. Ford:** Additional points on cable design emphasizing those touched upon in the paper, were brought out as follows:

Up until about 5 years ago, the largest number of pairs in a cable was 1,212. This cable was laid up in the usual manner of reversed concentric layers. Need was felt for a cable of still larger number of pairs and the 1,818, strip-insulated, 26-gauge cable was developed employing the novel idea of first laying up the pairs in bundles or units of 101 pairs and then stranding these units together into a cable. Mechanically, this makes a very satisfactory construction for such a large number of fine wires, enabling the obtaining of a cable which will handle well with little take-up in the stranding. Also since it is a common arrangement to have color groups of 101 pairs each, having the color groupings entirely separated in the cable, layup is of advantage. Pulp insulated wire seems naturally to fit very nicely into this unit idea and the construction has been standardized for 24-gauge as well as 26-gauge pulp cable and is just being applied to 22-gauge pulp cable.

Pulp has not as yet resulted in a new line of cable but in a new type of an existing series of No. 24 and No. 26 exchange area cables which are lower in first cost and compare very well in quality with the ribbon insulated cables which they displace. That is, in the cables so far standardized, the idea has been to make the pulp cable match as nearly as possible cables which had been developed with strip insulation, the gain in cheaper construction and the specific dimensions of pulp insulated cable given under the heading, Cable Design, apply of course, only under these conditions. As stated in the paper, pulp admits of a considerable range of values in weight and diameter and no doubt, advantage will be taken of these in the future which will likely result in an entirely new type of cable.

Some of the principal questions asked were as follows:

1. What are the merits of Jack Pine *versus* spruce as a stock for pulp insulation?
2. What flexibility could be expected from a wire insulated with a thick wall of pulp?
3. How does the wall thickness of pulp compare with strip insulation?
4. Because pulp cables are harder, could not pure lead sheath be used instead of lead antimony sheath?
5. Why was not the core impregnated with some material, such as paraffin?

Answers to the above questions follow:

1. Spruce Kraft is a cleaner, stronger and more expensive pulp than Jack Pine Kraft. It works somewhat better on the machine and has particularly good sheet forming characteristics. This tends to give a better insulation from the standpoint of appearance and uniformity, but experience of several years has indicated lower capacitance in cables made from a Jack Pine Pulp and as this quality is of prime importance, Jack Pine is considered standard at present. This capacitance difference has so far not been explained by the fiber characteristics.

2. A thick wall of pulp would have the tendency to be rather stiff and inflexible, especially when dry and would not admit of being bent on a short radius without injuring the insulation. It would not be as flexible, as for example, an insulation of the same wall thickness of cotton servings.

3. For 24-gauge wire, as an example, the common thickness of strip paper is 0.0025 in., the paper is applied helically with appreciable overlap and with a considerable air gap between it and the conductors so that its mean diameter, as it is insulated, is of the order of 0.045 in. Correspondingly, 24-gauge pulp covered wire is insulated to a diameter of about 0.041 in. with practically no space between the insulation and the conductors, making the wall thickness a little less than 0.011 in.

4. Whereas the insulation on the conductor is more firm for the pulp in comparison with strip, the cable cores as constructed are not particularly different in this respect. Furthermore, the composition of sheath used in Bell System telephone cables, is in no way related to the firmness of the core, lead antimony being universally used for land cable. Lead antimony cable sheath has demonstrated itself to be especially suitable for aerial cables having much longer life than pure lead and costs but little more.

5. For telephone circuits, a dry unimpregnated insulation gives the most efficient dielectric. Impregnations are not required to obtain high dielectric strengths and dry insulation of low density gives the best capacitance and conductance factors.

# Use of Cables for Telephone Distribution Purposes

BY M. C. ROSE* and H. A. RUSSELL†
Associate, A.I.E.E. Non-member

***Synopsis.***—*The paper outlines the uses of telephone cable for distribution purposes in typical metropolitan areas, such as Baltimore and Washington. It includes some historical background as to the development of cable and the part it takes in the present overall plant investment. The division of metropolitan areas into central office areas and the various types of distribution are discussed. The engineering procedure followed in the design of cable distributing plant to provide economically a metallic circuit of satisfactory transmission quality to connect each subscriber's telephone with the central office involves the consideration of many factors.*

## INTRODUCTION

IN the early days of the telephone art due to the small numbers of telephones then in service, it was feasible to furnish telephone service by means of overhead wire construction, as shown in Fig. 1. In present day typical metropolitan areas, however, such as Baltimore and Washington comprising from 140,000 to 180,000 subscribers' stations where a separate pair of wires is required to connect each individual line subscriber and every two 2-party line subscriber with the operating center or central office, it is clearly evident that aerial wire construction is out of the question from either a practicable or economical standpoint. The development of cable, therefore, containing large groups of insulated wire conductors in a common sheath having a reasonable maximum outside diameter has been and is the economical solution of the present day telephone distribution problem in the majority of cases.

As far back as 1882, the necessity for investigating the feasibility of underground construction, in advance of the time when the growth of the business in the larger cities would require the wires to be placed beneath the streets, was foreseen and the first considerable underground cable experiment was conducted. By 1892 a maximum of 100 pairs of wires were included in lead-covered cable. Subsequent developments brought this, in the United States, to the present maximum of 1,818 pairs of wires included in a common sheath, having a maximum outside sheath diameter of about 2⅝ inches. The available sizes of cable cover a broad range and generally vary in increments of 101 pairs for the larger size cables and 26 and 51 pairs for the smaller size cables.

In areas such as Baltimore and Washington, the investment in cable plant represents about 25 per cent and 21 per cent respectively of the total telephone plant investment. The following table shows a comparison of the total amount of cable in plant at the end of 1931 with that of 10 years ago.

| | Millions of conductor feet of cable in plant | | |
|---|---|---|---|
| | End of 1931 | End of 1921 | Increase 1931 over 1921 |
| Baltimore | 3,051 | 1,362 | 1,699 or 123% |
| Washington | 3,290 | 1,500 | 1,790 or 120% |

It is interesting to note that the increase in the amount of cable in plant has been appreciable in the past decade. At the present time the average length of cable pair serving each subscriber is 1.1 miles and 1.2 miles in Baltimore and Washington, respectively.

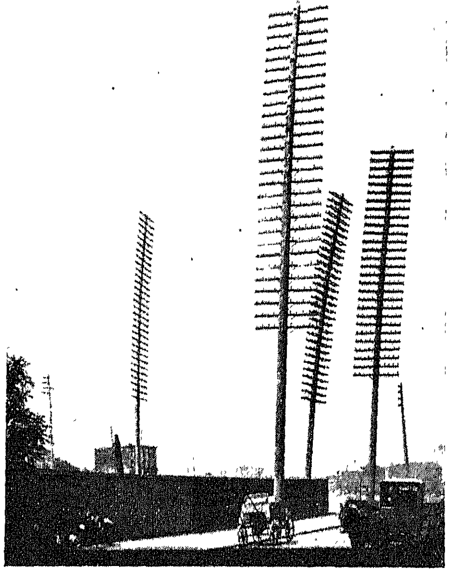

FIG. 1—OVERHEAD WIRE DISTRIBUTION IN THE 90'S

## GENERAL DESCRIPTION OF TELEPHONE DISTRIBUTION SYSTEMS

*Metropolitan Area.* Metropolitan areas (Fig. 2) such as those under discussion must, due to their size, be sub-divided into smaller operating areas, known as central office areas, each containing an operating center at or near the wire center. The central office may be defined as that part of the exchange plant housed in one building while the wire center is that location at which the cost for subscriber lines and interoffice trunks will be at a minimum. The choice of the number of

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exchange areas and locations of the centers is the result of economic studies involving population trends, community of interest, volume of traffic, expected growth, first cost and annual charge comparisons, etc., generally based on a long term program of from 18 to 20 years. It is usually uneconomical to serve a city having a population of over 100,000 from one center because of the long circuits necessary to reach the more distant subscribers, with the resulting use of costly larger gage cable conductors to meet transmission requirements. On the other hand it is equally uneconomical to go to the other extreme and set up a large number of operating centers which require heavy initial investments in land, building, and central office equipment and consequent large operating costs. A happy medium is to establish sufficient centers to more nearly fit the present condition and care for expectations for growth on a sound economic basis.

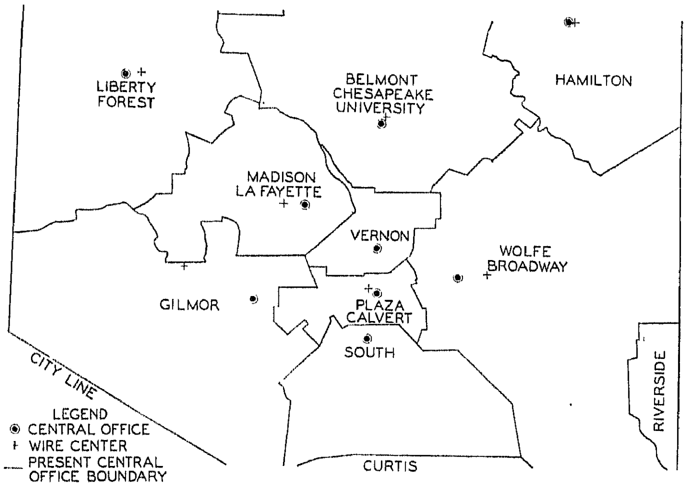

FIG. 2—SECTION OF METROPOLITAN AREA SHOWING CENTRAL OFFICE AREA BOUNDARIES AND CENTRAL OFFICE LOCATIONS

Note: Vernon Plaza-Calvert and South will ultimately be served from one office

Cable is used to interconnect the central offices for trunking purposes and to reach subscribers within the exchange areas, the latter usage being the one in which we are particularly interested in this discussion.

*Distribution in a Typical Exchange Area.* The subscriber cables, *i.e.*, the cables connecting the subscriber with the central office, terminate in the central office on the main distributing frame (Fig. 3) where the cable pairs cross-connect to cables which extend to switchboards and other central office equipment. These terminating cables enter the central office through what is known as a cable vault (Fig. 4) generally consisting of a space apportioned off in the basement under the main distributing frame to permit orderly racking of the cables and to provide adequate space for working on the cables, such as splicing. Cables radiating from the central office are generally underground at least in the main feeder routes through areas of heavy subscriber line density, in congested sections, and in locations where franchise requirements or rights-of-way and physical difficulties will not permit overhead construction. Underground feeder cables are connected at their outer ends to the various types of distributing plant such as aerial, block or house cables, dependent upon the type of area to be served.

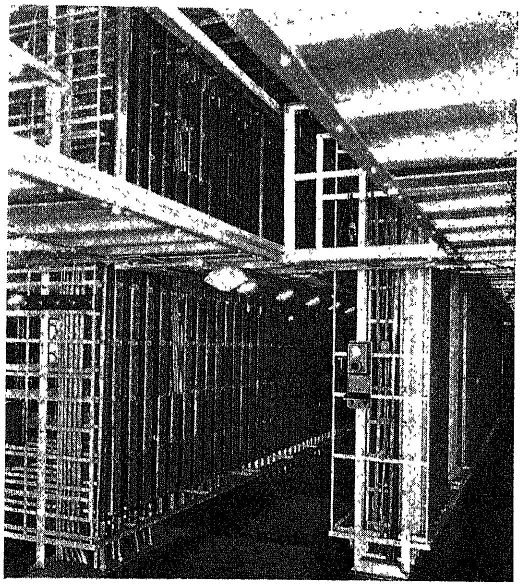

FIG. 3—TERMINATION OF OUTSIDE CABLE PAIRS IN CENTRAL OFFICE AT MAIN DISTRIBUTING FRAME

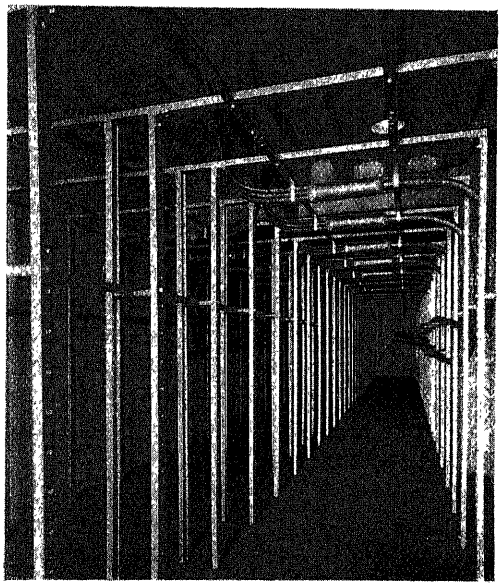

FIG. 4—CABLE VAULT

Exchange areas are of two general types, namely the downtown business and the residential, based on development characteristics and type of building construction. From a telephone standpoint the business areas comprise built-up blocks including department stores, apartment houses, hotels, office buildings, manufacturing plants, warehouses, large retail stores, etc., where the station density is relatively high. The residential areas, on the other hand, are those less densely occupied. They may contain some neighborhood business and may have either the high or the medium class of residences predominating.

*Downtown Areas—Main Feeders.* The cable plant in the downtown area includes a large number of feeder cables, serving both the downtown area itself, and the residential areas beyond. The larger size cables containing the finer gage conductors are placed nearest to the central office to permit the maximum efficient usage in the area of greatest station density and to utilize the minimum number of cables and ducts in the subway. The physical aspects of convenient cable handling and construction features limit the conduit sections in main line subways to about 650 feet. Subway sections are often shorter than this, however, due to lateral branches, to distributing points or to the particular design of the subway system to meet the physical problems encountered, such as layouts of streets or alleys, changes in grades, etc. Cable sections in the main line subway are made continuous by splicing them together in the manholes. Where branch or lateral cables (extended from a manhole) are to be terminated a cable stub is used, which consists of a short piece of cable, one end of which is spliced to the main cable and the other end spliced to the branch cables. The purpose of the stub is to provide a means of adding to or rearranging the branch cables without opening the main cable splices, an objectionable procedure due to causing possible cable troubles and future costly rearrangements.

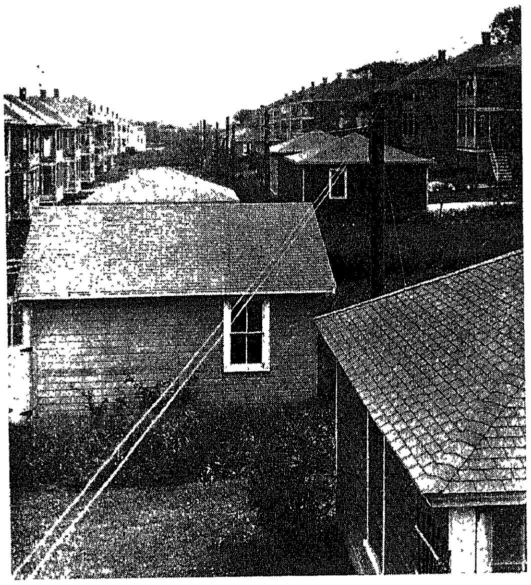

FIG. 5—AERIAL CABLE DISTRIBUTION IN RESIDENTIAL AREA

*Block Areas.* Branch or lateral cables connect the main feeder cables with the block, house or aerial cables which distribute within the block or blocks or within the buildings in the block. Cable used for overhead distribution consists of the same type of material as is used for underground construction and is termed "aerial" when it is strung on poles, "block" when attached to building walls, etc., and "house" when used for distribution within a building as shown in Figs. 5, 6 and 7.

Block cable distribution is generally considered in areas of high station density such as financial, mercantile, hotel and apartment districts. Since block cable is attached to building walls a large portion of it with its associated terminals is often in inaccessible locations and expensive to maintain. This type of plant does not possess the flexibility of aerial plant, and is subject to frequent rearrangements whenever any building changes are made.

*Residential Areas.* While some block cable distribution is necessary in the congested and neighborhood retail section of residential areas, the majority of the areas are served by aerial cable. The residential development is generally of the row house, semi-detached house or detached house type with well defined alleys, rear property lines or streets which lend themselves to rear property or street distribution. Rear property or alley distribution is used in fairly well developed areas while street and highway distribution is used in areas of low density where the width of streets is such that higher poles and longer drops from the cable to the subscriber's station are not required. The choice between aerial and underground cables for feeder routes in these areas is not entirely dependent upon relative costs but takes into consideration the character of the community, period of usefulness of aerial plant, flexibility of aerial plant, permanency of underground plant and expected growth, bearing in mind that pole lines are generally designed to carry not more than two maximum sized cables.

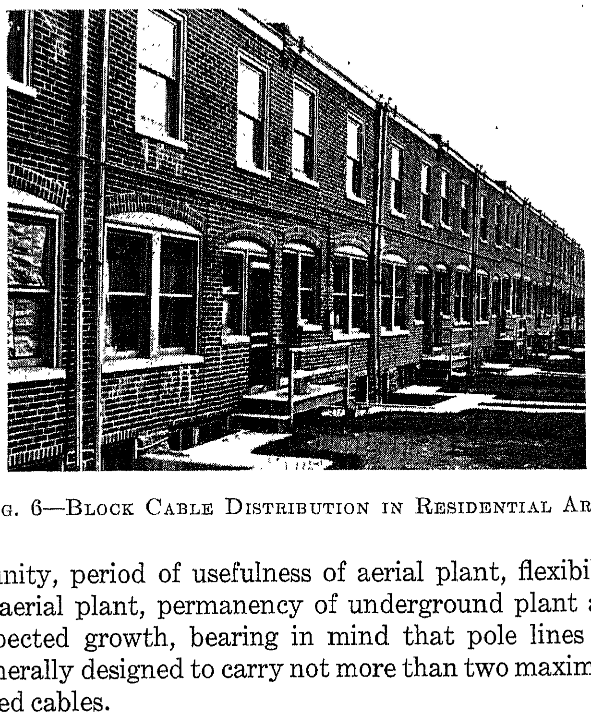

FIG. 6—BLOCK CABLE DISTRIBUTION IN RESIDENTIAL AREA

In the more expensive residential developments there is often, in addition to the lack of satisfactory locations for overhead distribution, a desire on the part of the property owner or the developer for underground distribution to improve the general appearance. For this type of construction cable suitably protected from soil erosion is buried directly in the ground without the use of conduit. Buried cables are generally located along rear property lines, along the edge of roadways or under sidewalk parkways, between the footway and the curb, and terminations are made by means of small terminals either in small underground concrete splicing boxes or in short pedestals above ground. One- or two-pair buried branch cables are used to connect the distributing cables with the subscribers' premises.

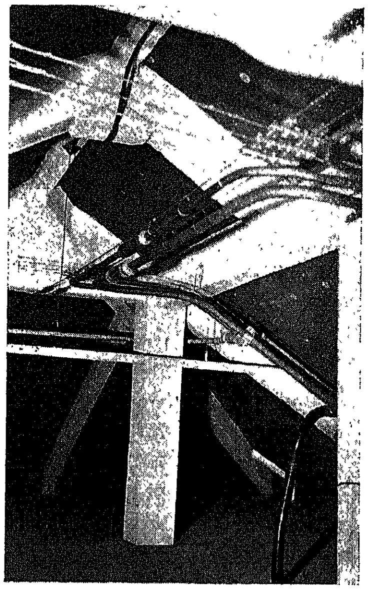

Fig. 7—Section of House Cable Run in Loft of Large Government Office Building

## Cable Plant Design

Problems involving cable plant design are relatively complex as compared with those for overhead wire distribution. Facilities must be provided to care for initial requirements and in sufficient quantities in the proper location to care for expected growth in the most economical manner. A complete system of records continuously maintained is absolutely necessary as basic data for successful design. The more important features embodied in economical cable plant design are given under the following three headings.

*Transmission.* The proper gage and type of distributing cable plant determined for any central office area is based on the maximum allowable loss in the distributing plant in that office area. The allocation of losses between the distributing plant and the trunking plant is determined by economic studies, made from time to time as changing conditions warrant for each exchange area. As a result of these, the permissible limit of subscriber's loop, that is, the permissible total of transmitting and receiving losses are established for the subscriber's station equipment, the pair of wires connecting the subscriber's station to the central office and the associated central office equipment. The central office equipment loss is practically fixed except for certain cases where lines require special equipment, but the loss between the central office and the subscriber's station can be controlled by varying the gage of the cable pairs used. Also several types of subscriber's station equipment are available, some of which are more efficient than others. The design of distributing plant, therefore, involves the choice of the proper gage of cable conductor and type of subscriber's station equipment to most economically bring each subscriber within the loop limit of the exchange area involved. Fig. 8 shows the gage limits for various central office loop limits. The gages of conductors commonly employed in distributing cable plant are 26, 24, 22, and 19 or a combination of any two. The smallest gage conductors consistent with the allowable length of loop are used as a permanent and most economical arrangement in feeder and distributing plant nearest to the central office; however, larger gage conductors are sometimes used as a temporary expedient to defer placing additional cables in feeder and distributing plant nearest to the central office, and at other times to defer placing additional cables in feeder routes until relief is neces-

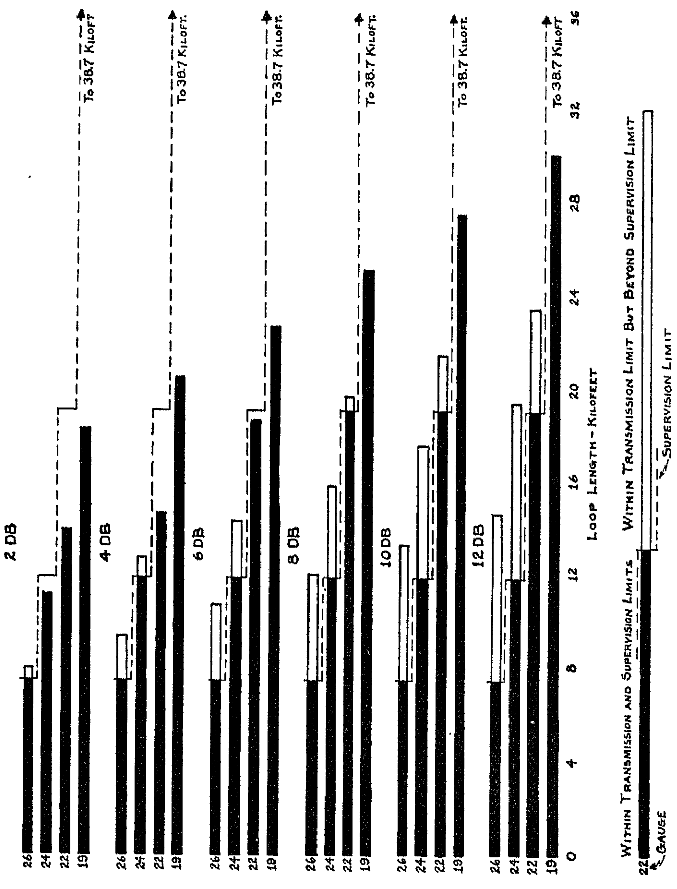

Fig. 8—Gage Limits for Various Central Office Loop Limits Nos. 1, 10, 11 or Panel Type Office—Local Connection

Handset and anti-sidetone station circuit sary. Combinations of two gages are often used to effect economies in areas between the limits of these gages by making the fullest use of the smaller gage conductors.

*Flexibility.* Certain groups of pairs or complements are terminated at frequent intervals throughout the cable length to provide for wire connection to the subscriber's station by means of splicing to the group of cable pairs to be terminated, small distribution terminals ranging in size from 11 to 26 pairs. The location of terminals, either on poles or building walls, is determined directly by the number and locations of stations to be served and the relative economy of establishing terminals as compared with paralleling the cable with aerial wire for short distances.

It is quite obvious that in order to provide cable plant economically and have points of termination available to care for either individual or party line service at any desired location, the number of cable pairs terminated in the total number of distributing terminals will exceed the actual number of pairs in the distributing cables. In a like manner the total number of cable pairs in the distributing cables will generally exceed the number of pairs in the feeder cables. This makes it necessary to overlap or multiple the pair counts in the distributing cables and also in the terminals. In cable work this term indicates the repeated or multiple termination or grouping of the same cable pairs at more than one location and is often more broadly applied to any arrangement of cable pair terminations or groupings, even though no actual repetition occurs.

Cable is manufactured with paper or pulp insulation on the conductors in various combinations of colors so that groups of conductors have the same identifying colors throughout. Each cable pair is assigned a number at its termination and each group of conductors assigned a count, such as 1-101, 102-202, etc., in order to keep a record of the usage of each cable pair, for line number assignments, splicing, maintenance, and to facilitate engineering.

The multipling of cable pairs and counts offers almost unlimited combinations, but practical considerations and operating features usually narrow the field to comparatively few feasible plans. The choice of arrangements must, therefore, carefully consider present and future requirements and in general aim toward the following objectives:

1. Terminate all cable pairs to make them available where they will be needed.
2. Terminate all cable pairs to conform with plans for future relief.
3. Minimize unavailable cable pairs.
4. Make the same cable pairs or count available a sufficient number of times to permit the best possible use of the circuits.
5. Permit simple records, facilitate line number assignments, fault location and trouble clearing and simplify engineering of facilities.

In designing multipling, it is necessary to start with the distribution terminals and cables where requirements are fairly definite. The sizes of the cables having already been determined and estimates made of the ultimate number of stations to be concentrated at each terminal location; the terminals and distribution cables are grouped to the best advantage. The basic principle in this operation is to apportion the available cable pairs to the several terminals in accordance with the number of stations the terminals will serve, due regard being given to the provision of overlap of terminal counts for purposes of flexibility and association of party line stations.

In the cases where distribution cables or distribution complements of feeder cables initially serve several ultimate areas, the section or complement of cable serving each ultimate area is considered separately and these complements are multipled to the best advantage. The pair counts in the distribution cables are next assigned to the aerial feeders, subsidiary and branch feeders and in the main feeders in such a manner as to use up the entire count of the feeder cable. The method of providing future relief, however, generally governs the manner in which this multipling is carried out to provide a minimum of future cable rearrangements.

In the overall results, the care with which the multipling is designed in the initial layout has an important bearing on the conductor usage and flexibility of the cable plant, on the economy of providing service for new business as required, on the provision of and relief to existing cable plant when capacities are reached.

*Planning New Cables and Provisions for Relief.* The requirement for cable is generally associated with one of the following factors:

(a) To provide for anticipated telephone service in an area where no cable facilities exist.

(b) To supersede existing aerial wire distribution where warranted by demands for additional service, or expectations of growth, or due to physical or right-of-way conditions involving the existing aerial wire construction.

(c) Cable of one type of construction superseded by that of another type due to physical or right-of-way conditions.

To meet the conditions in (a), the immediate requirements together with the expected rate of growth generally determine the practicability of placing cable *vs.* wire. Where any doubt is evidenced, the decision rests on the results of cost studies.

In (b) the relative economies determine the course of action where local conditions are not a factor; however, in both (b) and (c) where unavoidable conditions have arisen since the initial route was established, the best engineering solution, taking into consideration the choice of alternate locations, is the answer to the problem.

A study of the records permits a tentative determination of the area to be served and the route to be followed by the proposed cables. Since the initial design is based upon the requirements for the initial area to be served and certain assumptions as to future action, it is also necessary to select at this time the ultimate area to be served by the proposed cable in order to determine the steps to be taken in the future to provide relief. Deviations from the initial routes selected are sometimes necessary, but in the majority of cases underground routes are pretty generally established and most aerial feeder routes are the outgrowth of preceding aerial wire lines.

The number of conductors or the size of a cable for any specific case is one of the most important features of cable design and is dependent directly upon the maximum fill and economic period of fill. The maximum fill is the total number of pairs in a cable that may be used economically without serious interference with the continuity of the service. The economic period of fill is largely controlled by the expected service life, *i.e.*, the average length of time cables remain in plant, and the method of future relief. When these conditions are known or definitely assumed this factor may be determined from cost studies and in the average case is generally from about 1/3 to 1/2 of the service life of cable. Cables are diminished in size through the distribution area rather than placed in continuous size in order to minimize the cost of the cable plant and to obtain the most efficient operation without penalizing its flexibility.

## BUILDING CABLE DESIGN

In considering the problem of furnishing telephone service to large buildings, it is quite impracticable and uneconomical to place a pair of wires through the building each time a telephone is required. Buildings of these types are generally given service by means of house cable which is placed in the building during its construction, and provides facilities which will permit convenient and efficient connections of telephones at any location within the building. The house cable system is usually designed to meet the maximum requirements of the building with sufficient flexibility to care for any changes in the relocation of the telephones or for any rearrangements to the building.

These systems usually consist of one or more riser cables starting directly from an entrance cable or from a main cross-connecting terminal or frame, in the basement, and extending up through shafts or conduits of the building. Branch cables on each floor are terminated at suitable distribution points by means of floor terminals, where connections are made to the subscriber's telephones by wires.

The general arrangement of the house cable system is almost identical to the general outside plant arrangement in a central office area in that the riser cables may be likened to the main underground cable, the floor branch cables to the subsidiary distribution cables and the floors themselves to individual blocks or areas along a feeder route.

## CLASS OF BUILDINGS

For the purposes of house cable design, large buildings are put into one of two classifications, depending upon the expected permanency of stations, both as to number and location, as follows:

*Office and loft buildings* in which telephones do not remain fixed either in number or location for any extended period but vary with the requirements of the individual, who will use more or less telephone service according to respective activities; or

*Hotel and apartment houses* in which the number and location of telephones are fairly definitely fixed by the number and arrangement of rooms or apartments in the building and the telephone service required by successive occupants is approximately the same.

## PLANNING FOR REQUIREMENTS

Close cooperation is necessary between the telephone engineer and the owner, architect or contractor in order that the house cable system may be designed to conform to the building layout, and in order that the building plans may include the provision, by the owner, of the necessary shafts, conduit, cabinets and other housings for that house cable system.

Unless suitable housing facilities are provided in advance for accommodating cables and wires and for passing them through the walls and floors, either exposed telephone installations will result in unsightly conditions, subject to possible damage with subsequent undesirable effects on service or extensive costly alterations may be required after completion of the building to conceal effectively all cables and wires. These systems of housing facilities include cable and wireshafts, conduit boxes, molding raceways, underfloor ducts, etc., and are designed to conform to the maximum requirements in common with the water, gas, electric light and power conduits as an integral part of the building. The vertical accommodations (for the riser cables) start from the basement and rise to the top floor connecting at the various floors with horizontal housing facilities, and junctions between cable conduits are effected by means of splicing closets or splicing and terminal boxes whereby complete passage is afforded for cable and wire from the basement to the location of the station.

Consideration is given to the intended present and future use of a building, the character of its location and average rental value in order to design the cable plant to meet the conditions. Experience has shown that maximum circuit requirements have a definite relation to rentable or productive floor area and this relation is the basis for both house cable and housing system design. Pair density factors expressing the relation between rentable or usable floor area and cable pairs provided have been developed for certain cities by an analysis of the use being made of house cable in existing buildings. From these data broad averages have been derived in the form of ranges of the number of riser cable pairs per unit of floor area which would provide liberal facilities for the developments realized. These factors are used in determining the amount of facilities to be provided in any particular new problem by applying them to the rentable or usable floor areas.

### CABLE ENTRANCE AND MAIN CROSS-CONNECTING TERMINALS

The cable entrance point is selected with the object of establishing the shortest satisfactory route from the point of connection with the feeder system. Cables are preferably attached to walls or ceilings rather than to partitions which are subject to removal or changes. The number of entrance cable pairs to buildings not served largely by one or several local switchboards is determined in the same manner as the facilities to be provided within the building. The number of entrance cable pairs in a building having private branch exchange service is designed to meet the requirements of one or several switchboards, that is, provide trunk lines, telephone power lines, and facilities for outside extensions, if any, including a surplus of pairs to insure adequacy and also provide central office feeders for stations other than extensions on the switchboard. In some cases the building entrance cable includes facilities for extensions to the adjacent block plant.

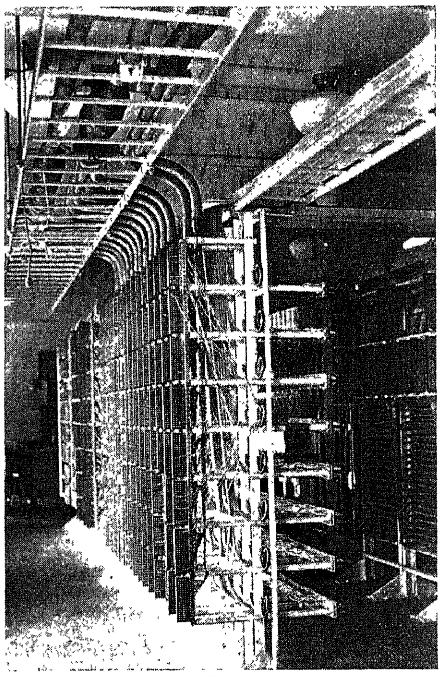

FIG. 9—CROSS CONNECTING FRAME IN BUILDING

The main cross-connecting terminal or frame, shown in Fig. 9, is usually in the basement at or near the foot of the riser shaft or conduit. The specific location should be determined upon in advance of the building construction in order that the required space may be set aside and the necessary housing accommodations be installed as the building is erected.

### RISER CABLES AND HOUSINGS

Riser cables (Fig. 10) are designed as nearly as practicable to intersect the floors at the wire centers as determined by study of the typical floor plans. Specific location for the riser cable housing is preferably a permanent corridor partition or in the wall of some public place leading from the corridor and easily accessible without annoyance to the tenants of the building.

In buildings having large distribution areas or in which each floor is made up of several distinct distribution areas, two or more riser systems may be desirable, each being used to serve a definite floor area centering about it. In office buildings containing several riser systems, these systems are tied together at certain floors with conduit of sufficient size to house a cable containing enough pairs to permit concentrating the entire floor system on any one riser.

### FLOOR CABLE AND WIRE HOUSINGS

Floor cable and wire housings in combination, afford passage for the telephone circuits from the riser system to the approximate locations of the individual telephones. Cable housings extend more or less directly from the riser to wiring centers on the floor where floor distribution terminals are located and where connection is made with the housings for wire. The floor cable housing system must accommodate a floor distribution cable plant which provides adequate facilities to meet the demand for telephone service on the floor wherever and in whatever quantity it may be. The first step in

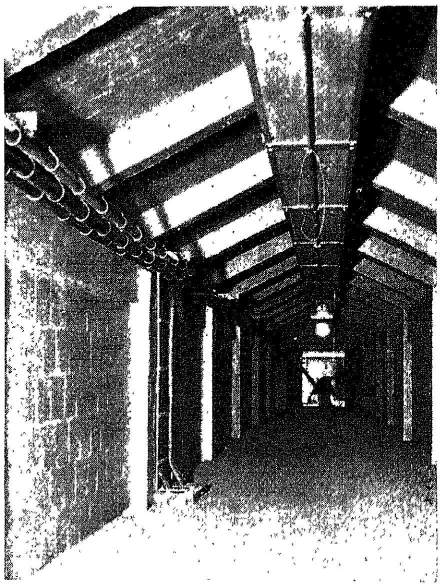

FIG. 10—SECTION OF HOUSE CABLE SYSTEM IN LARGE GOVERNMENT OFFICE BUILDING

Showing type of riser cable shaft in loft of building and riser cables the design of the system is the determination of the number of cables including terminals which it will house, their location and size. In small buildings, where the amount of floor distribution is not extensive, the housing system may carry cables and wires together in such raceways as hollow moldings or baseboards. In most buildings, however, separate systems for cable and wire are necessary, although it is usually quite practical and economical to place small cables in lieu of wire in housings intended for wire when special distribution requirements make this desirable.

## CONCLUSIONS

Telephone subscriber cable plant engineering is responsible for the provision, in the best practicable way of the wire plant facilities for rendering telephone service where ever it may be desired within an office area. It also has the responsibility for designing an efficient cable plant. The provision of telephone service by open wires on pole lines would have the advantage that the plant, so far as the wires are concerned, would be operated at a high degree of efficiency. Each pair of wires would be placed as required and extended only as far as required, and little or no idle plant would exist. This is obviously impracticable with cable plant. Facilities in cables must be placed in advance of requirements, and single pairs cannot be ended at the point where they will be used, assuming that this could be determined in advance. Consequently, a considerable portion of the conductors in the cable plant are idle, or spare. It is essential, from the standpoints of both economy and readiness to serve, that this spare margin be maintained within recognized limits. This is a function of cable plant engineering, the control being through the selection of proper sizes of cable and in the provision of flexibility as by cross-connection, multipling, etc., as discussed in the body of the paper.

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## Discussion

**J. A. Cadwallader:** In connection with the buried cable distribution a description of a system recently installed in a high class residential development near Pittsburgh, Pennsylvania, may be of interest.

The development embraced an area of approximately 30 acres subdivided into 155 building lots which were irregular in shape and fronted on curved and winding streets. The land company was desirous of eliminating aerial plant from this development and approached the utility companies with that end in view. The results of cooperation between the Telephone Company and the development company resulted in the design of a buried cable distributing plant involving the following:

(a) The land company reserved a 10-ft strip along the rear property line for the utilities, provided the trench for the cable and excavation for the splicing boxes.

(b) The individual property owners provided a conduit from the house to the nearest splicing box.

(c) The Telephone Company furnished and installed tape-armored distributing cable, splicing boxes and terminals and one or two pair lead-covered cable in the conduits from the splicing boxes to the houses for connection with the subscriber's stations as required.

The plant involved included, in addition to the one and two pair lead-covered cable, about 4,300 ft of 26 to 202 pair 24-gauge tape-armored cable and 21 splicing boxes. These splicing boxes were of precast concrete reinforced with wire mesh and about 26 inches long, 16 inches wide, and 18 inches deep with 2 inch walls.

The entire cost of this distributing system to the Telephone Company approximated very closely the estimated cost of an aerial cable job using pole plant jointly occupied with the Electric Light Company.

**L. F. Cromwell:** I should like to emphasize the importance of careful cable pair multipling in the design of the cable plant to effect a minimum plant investment and minimum annual charges, consistent with good service. It must be borne in mind that every dollar invested in plant carries with it these annual charges as long as it remains in plant. It is necessary, therefore, to guard against too liberal provision of plant.

It is in the engineering of the cable layout and in the selection of the types of materials that the real economies lie. The effectiveness and efficiency of an otherwise well designed cable plant layout may be defeated by lack of thorough consideration in the multipling of either distribution or feeder cables.

The selection of a sound multipling system is essential to ensure permanency and to avoid too liberal provision of plant. Such a system also facilitates the maintenance of clear, concise records and simplifies engineering, assignments, and trouble locating and clearing. The efficiency of the cable or cable plant can be determined by a study of the cable usage. One index of cable usage is known as "pair mile efficiency" which may be defined as the ratio of the conductor feet, or other unit length, of circuit required to serve all stations, to the conductor feet, or other unit length, of circuit actually provided in the cable or cable plant. Pair mile efficiency is largely controlled through the selection and distribution of cable sizes and the multipling of cables.

In a well designed aerial wire plant each circuit is extended only to the farthest station on that circuit. Such a plant, therefore, has 100 per cent pair mile efficiency as well as 100 per cent of its conductors in use.

A cable plant must provide many circuits in advance of requirements and the number of circuits can be reduced only at a comparatively few points in the route and not at each point where the capacity of any circuit is filled. Such a plant cannot have either 100 per cent of its circuits in use or 100 per cent of each circuit in use. Careful planning will, however, assist in obtaining and maintaining high efficiencies. The nearest practicable approach to aerial wire plant conditions is in the use of diminishing cables.

When selecting the multipling system it is necessary to anticipate the successive steps to be taken when subsequent relief for the cable plant is required. Permanent relief can be provided either by reinforcing, replacing or dividing the congested cable, while temporary relief can be provided by making cable transfers to remultiple the cable pairs or by the installation of cross-connecting terminals.

For example, in designing a feeder cable, which is to serve initially more than one ultimate area and which will subsequently be relieved by dividing, it is essential to determine the "points of relief," *i. e.*, the points at which the initial cable may later be cut or divided.

If these points are established to meet a definite estimated growth, the multipling of the cable may be so designed that no rearrangement of branches will be required in connection with successive relief plans, unless the actual growth realized differs appreciably in either location or amount from the predicted growth. Such a layout in reality consists of the repeated assignment of the entire feeder cable pairs to the distributing plant in each area, so that when the cable is initially spliced at the "points of relief" into one continuous cable it will be the same as one cable superimposed upon the other with no conflict between cable pairs in use. This superimposing must also provide for a reasonable number of spare cable pairs for future use in all terminals. When relief is required the installation of an additional cable to the "point of relief" will provide separate feeder cables for the two sections of the original cable.

Cable transfers consist of transferring one or more terminals, distribution or branch feeder cables from certain cable pairs in one cable to other pairs either in the same or a different cable. The result of this plan is a redistribution of both existing lines and provision for expected growth in existing cables, thus making idle pairs available where they can be used to the best advantage.

The real test of cable pair multipling is not encountered when the installation is first completed but when service has increased to such an extent that the cable has a majority of its pairs in use. At that time, in some cases, especially when the growth has not been distributed as was anticipated, relief can be provided by cable transfers which increase the flexibility and defer cable extensions or reinforcements.

**C. L. Garrett:** In furnishing satisfactory transmission, not only must the speech be received with satisfactory volume or loudness but factors which may tend to reduce the intelligibility must be considered and allowance for these factors made in the design of the plant. These factors include noise, crosstalk and distortion, and some of them can, to a certain extent, be counteracted by an increase in volume.

There are two general types of noise which cause objectionable interference. One, which is known as line noise, is due to currents induced in the telephone circuit by neighboring telephone and power circuits and the other is room noise. The detrimental effect of room noise is twofold; first it directly enters the ear of the listener thereby distracting his attention and, second, it reaches the transmitter and sets up currents in the station equipment which produce noise in the receiver thereby affecting the intelligibility of the received speech. In a metropolitan area where most of the distribution plant is in cable and the circuits relatively short, room noise is the most important.

As brought out in the paper several types of subscribers' station instruments are available for desk stands, the principal differences being in the characteristics of the transmitters. For use on low resistance subscribers' loops, sturdy transmitters capable of handling relatively high currents are employed. With the increased use of small gauge cables it was necessary to introduce highly efficient ones designed to operate on small current flows. These latter types, however, do not perform well on the short loops and are harmed by too large current flows. In order to control the use of the various types and at the same time bring all lines in an area within the loop limit with the maximum average efficiency and economy, it is necessary to set up zones in which the different types of instruments available are to be used. However, in the determination of a practical zoning system, several things must be considered in addition to the theoretical limits. For ease in administration the system should be simplified as far as practicable by keeping the number of zones to a minimum and selecting simple, readily located, geographic boundaries for them. In addition, the supply situation must be considered and alternate types of instruments prescribed for zones, where this is practicable, in order to provide a suitable field for the re-use of instruments recovered from the plant. To make the information readily available, maps are usually prepared for each central office area showing the geographic zone boundaries and the types of instruments permissible in each zone.

The distributing plant design is usually based on a maximum condition of transmission which all loops in the area tend to approach. Under this condition it naturally follows that the average value of transmission in a central office area is somewhat better than the limiting value. However, the extended use of the smaller gauge cables and the introduction of instrument zoning practises, together with the fact that losses are introduced by the presence of bridged taps, which are necessary in order to have a flexible layout, tend to make the transmission loss of the average loop approach the limiting value. In many cases there are in a central office area a limited number of extra long lines for which special treatment is required in order to provide transmission within the loop limit.

In addition to the furnishing of satisfactory transmission, the signaling and supervisory limitations of the equipment must be considered when designing the distributing plant. In a metropolitan area, the telephone system is operated on a common battery basis, that is, direct current is supplied from the central office over the cable pair to the subscribers' instrument. In order that sufficient current may flow to operate the supervisory relays at the central office, increased expense for special equipment is involved if the resistance of the subscriber loop exceeds a definite value, the resistance of the central office and station equipment being nearly constant. Referring to Fig. 8 of the paper, it may be seen that in some cases the economical use of the smaller gauge conductors is restricted because of this supervision limit and if only transmission were considered it would be possible to extend these gauges for an appreciably greater distance.

# Electrical Testing in a New Rubber-Covered-Wire Plant

BY C. W. PROTZMAN*
Non-member
and
W. M. HILL*
Associate, A.I.E.E.

## GENERAL

EFFORTS in the past decade to increase plant efficiency have resulted in a trend toward the development of more satisfactory means of testing the insulation of rubber-covered wires in quantity production, than the standard water test.

This has led to the consideration of various means for more rapid testing and to the evolution of direct testing methods to overcome the disadvantages inherent in the water test. These have not been generally adopted as yet however, and this paper therefore deals only with problems related to the testing of telephone wires and the results obtained.

## PURPOSE OF TESTING

The purpose of any electrical test is, of course, to locate such defects or potential defects as might cause failure in service. A satisfactory insulated wire from an electrical standpoint is one which will withstand the stresses to which it is subjected in normal service, and which will function over a long period of time without failure due to a defective insulation. To insure such service, tests must be made which will simulate in severity the most rigorous conditions encountered.

So far as telephone wires are concerned insulation defects may show up in either of two forms: (1) as a complete breakdown, or (2) as a low insulation resistance.

Among contributory factors in the development of weakened insulation are:

Presence of foreign material in rubber insulation such as: agglomerates of incompletely mixed compound ingredients, metal pieces, wood, vitreous material, textiles, etc.

Mechanical injuries to insulation including bruises, scraped or cracked insulation, and kinks.

Thin or uneven insulation resulting from process variations or defective equipment.

Holes or blisters due either to air bubbles in the compound or other causes.

## DESCRIPTION OF WATER TEST

The water test requires the immersion of the wire to be tested in a water bath for a minimum period of 12 hours before the test is applied.

This insures that the entire surface of the insulation is in contact with a conducting medium, and also that the water will have penetrated to the point in the insulation which would be most subject to breakdown or failure in service.

At the end of the immersion period an a-c. breakdown voltage is applied for a period of seconds, and following this a d-c. insulation resistance test is applied.

The first of these locates any points in the insulation which are sufficiently weak to cause breakdown in service, while the second determines whether the resistance of the insulation is sufficiently high to prevent leakage of current that would impair efficiency in service.

The usual method used for testing telephone wires is to apply the water test after the weatherproofing process. However, this test has several disadvantages among which are:

The water test requires a relatively large area for testing equipment.

The twelve-hour immersion period necessitates a large process stock of unfinished wire.

Continuous flow of material is prevented by the necessary delay of storing tested wire during a drying interval.

Separate testing and coiling or reeling operations are necessary, requiring more machines than would be required for a combined testing and coiling process.

The modern trend in manufacturing methods is to plan successive operations so that there are no delays, thus eliminating costly process storage. Combinations of operations with reduced machinery investment are also of prime importance.

## ENTRY OF WESTERN ELECTRIC COMPANY INTO WIRE MANUFACTURE

Several years ago an investigation was undertaken by the Western Electric Company to determine the possibilities of producing rubber-covered wire with a view to establishing improved methods of manufacture, thereby reducing the cost of telephone wires to the Bell System.

As a result of this investigation a new and faster method was developed, which combined the rubber insulating and vulcanizing processes in one continuous operation.

Prior to that time wire was insulated, packed in soapstone to prevent its sticking together, and was either coiled in pans or wound on drums, preparatory to a lengthy vulcanizing operation.

The radical departure of continuous insulation and vulcanization with its consequent reduction in operations provided a starting point for investigations to further improve and reduce the number of manufacturing operations.

An entirely new plant was erected so that it was possible to consider the most effective layout of equipment,

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*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

the best material handling methods, and the most economic storage plan, as well as to develop new machines and process combinations.

Among the processes which were studied to effect a simplification of operating methods the old plan of separate testing and coiling appeared to offer a fertile field for improvement as the water test and subsequent coiling operation were obstructions to the straight line production plan. It was evident that numerous advantages would accrue from the elimination of the water test and the combining of the testing and coiling operations if a quicker and more direct method could be substituted.

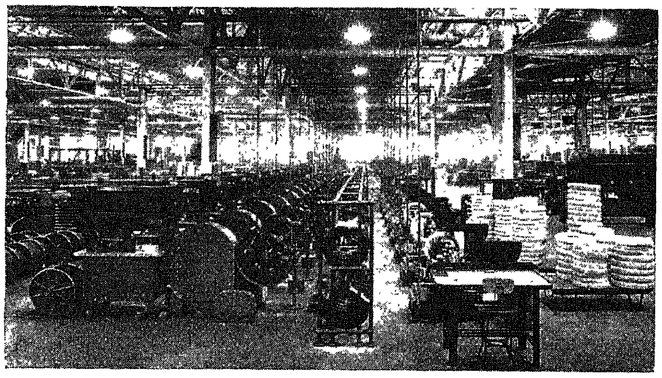

Fig. 1—General View of Spark Testing Equipment

The ideal test for this purpose would be one which would eliminate the following:

The necessity for accumulating stock during the testing and drying periods.

The relatively large area required for the application of the water test and the subsequent coiling operation.

The necessity for separate testing and coiling operations requiring two groups of equipment.

Before starting the development of a new testing process, the field of commercial testing equipment was carefully surveyed to determine whether any existing system could be located that would be adaptable to these plans.

The results of this survey and our own preliminary tests indicated that the equipment being introduced in several manufacturers' plants to locate and patch defects at the depanning operations could be modified and developed to fit our needs.

This equipment is of the dry or direct testing type which impresses a high a-c. voltage upon the outside of the insulated wire whose conductor is grounded. Thus the passage of a weak spot in the insulation through the high-voltage zone results in the formation of an arc from the electrode to the grounded conductor, causing a surge and the actuation of control apparatus to stop the passage of the wire and operate audible and visual signals.

The high a-c. voltage is obtained by means of a specially designed transformer of relatively low power and a condenser in the high-voltage circuit raises the commercial 60-cycle frequency to one of several hundred cycles when this circuit is suddenly closed.

The surge resulting from the arc at the passage of a defect through the electrode actuates the control apparatus in the low-voltage circuit in the manner described above.

The voltage is impressed on an electrode approximately five feet in length through which the wire passes before being coiled. The overrun of the wire due to the inertia of the supply reel as the solenoid brake is applied to stop it carries the defect beyond the electrode where it is accurately located by means of a hand electrode moved along the wire by the operator.

At the time of our investigation this equipment had not been used as a substitute for the water test and an extended development and trial period was necessary, to be sure that defects could be effectively located.

It should be noted that this test does not apply a direct check on the insulation resistance of the compound, but functions primarily to break down any weak spots in the insulation.

A trial unit was obtained which incorporated such features as were apparently required, although it was realized that adaptation to our process would probably involve a number of rearrangements and changes in the mechanical features.

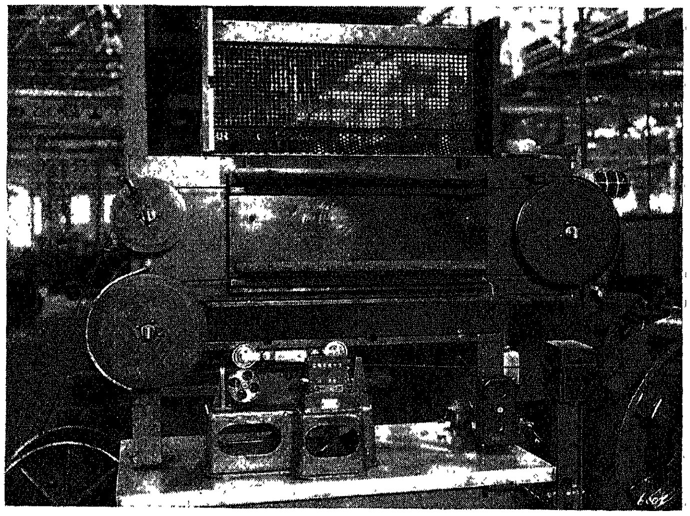

Fig. 2—Spark Testing Electrode, Stop Counter, Combined Wire Distributor, and Fault Locator

The testing transformer of this unit was supplied with secondary voltage taps ranging up to 15,000 volts, and after preliminary trials at various voltages it was determined that the critical voltage for No. 17 bronze parallel drop wire, upon which the tests were being conducted, was between 5,000 and 10,000 volts.

No. 17 BP drop wire consists of two insulated No. 17 gage bronze conductors laid in parallel under a single braid of cotton which is impregnated with a standard saturating and a finishing compound. The water test requirements for this wire are as follows:

| | |
|---|---|
| Breakdown | 1,000 volts a-c. |
| *Insulation resistance | 500 volts d-c. |

Tests were, therefore, conducted on the spark tester at the three available voltages, namely 5,000, 7,500, and 10,000 volts. Simultaneously a portion of each day's run of wire was water tested. This insured that the product submitted for each type of test was similar and that the number of defects located by each method would be most nearly comparable.

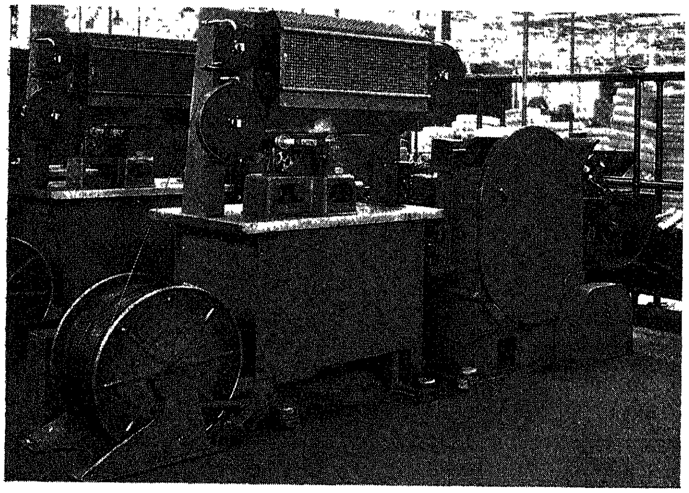

FIG. 3—RELATIONSHIP OF TESTING AND COILING UNITS

A length of 100,000 feet was arbitrarily set to serve as a basic unit for comparing the relative defects of wire tested by each method.

Data gathered in these tests indicated that the 7,500-volt tap produced results most nearly comparable to the water test for No. 17 BP wire, but in order to more closely determine the proper voltage another unit was provided with transformer steps of 1,000 volts, and further tests conducted at 6,000, 7,000, and 8,000 volts, as well as confirmatory checks at 5,000 and 10,000 volts.

The second set of data, based in each case on results from 1,000,000 pair feet of wire or more indicated that a 7,000-volt spark test located approximately the same number of defects per 100,000 feet of wire as the specified water test, and that a water retest of this spark test resulted in the failure of only 1.65 per cent of the product.

This was comparable to a failure of 2.75 per cent of originally water tested wire when subjected to a similar retest, and 7,000 volts was therefore established as the proper spark testing voltage. On this basis the spark test was adopted as standard for the testing of No. 17 BP drop wire.

It should be noted that the water test was necessary in establishing the proper spark test voltage to insure equally satisfactory insulation resistance and this test will continue to serve in establishing values for any particular type of insulation.

The adoption of the spark test greatly simplified our plans for the layout of the new plant, but due to special features required for our process, a number of changes was incorporated to improve the efficiency of operation and to increase the unit output, as well as to further reduce the floor space required. Some of the changes made are as follows:

A new electrode was developed incorporating a perforated lower plate or grid, and a pendant chain arrangement. The wire rides in a groove in this grid and the chain conforms to the upper half of the wire, and being free in vertical movement remains in contact with the wire throughout the entire length of the electrode. The lower slotted member permits loose wax to fall through to a hopper at the bottom of the electrode which is emptied periodically. This self-cleaning feature insures the correct test voltage being impressed on the wire at all times with a minimum voltage drop due to the collection of wax on the grid.

The electrode was split in half and the two equal lengths mounted one above the other with sheaves for reversing the wire, thus reducing the floor area required by approximately one half. The electric stop counter was placed directly beneath the electrode thus further reducing the amount of space necessary. (See Fig. 2.)

A fault locator built integral with the wire distributor at the coiling head, was added in place of the hand locator. The new locator is completely guarded to prevent any possibility of shock to the operator. Reference to Fig. 2 shows the present arrangement whereby a system of sheaves permits the placing of the supply stand against the electrode unit and the electrode unit close to the coiling head.

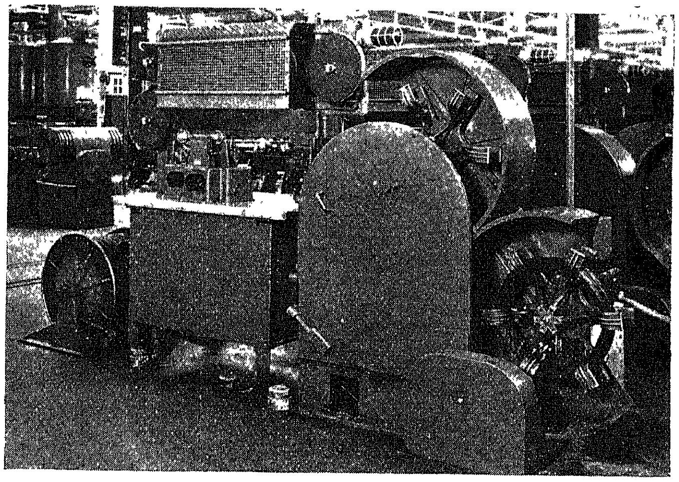

FIG. 4—TWO-HEAD COILING ARRANGEMENT

In order to produce a maximum of tested wire per unit, it was decided that a double coiling head arrangement should be provided so that the operator could tie one coil while another was being tested and wound. The arrangement of two heads at either end of an arm which is capable of rotation in a vertical plane, and on which the coiling head in the operating position could be positively engaged with the take-up driving mechanism was finally decided upon. (Figs. 3 and 4 show this mechanism.) Thus the machine automatically coils, measures, and tests wire continuously, save for the short interval required for the operator

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*With specified megohms at specified temperatures.

to rotate the heads, and connect the wire to the ground clamp on the coiling head for the next coil.

A control system comprising an arrangement of starting and stopping switches and foot control buttons for releasing the solenoid brakes on supply and take-up mechanisms has been adopted to reduce to a minimum any lost motion on the part of the operator.

To provide a foolproof mechanism which would insure that every coil completed was properly tested, the testing circuit and take-up drive mechanism have been electrically interlocked so that it is impossible to rotate the coiling head either by the take-up drive mechanism or by hand, without placing the test voltage on the electrode and fault locator. This is of vital importance in providing a satisfactory test.

In order that the operator may be protected from electrical or mechanical injury, the entire unit has been carefully guarded.

The take-up drive is made inoperative unless the guard over the coiling head is closed; the fault locator is placed in a phenol fiber case which prevents the operator receiving accidental shocks; the electrode is surrounded by a grounded metal guard, and moving members of the drive, as well as solenoid brakes, are properly guarded.

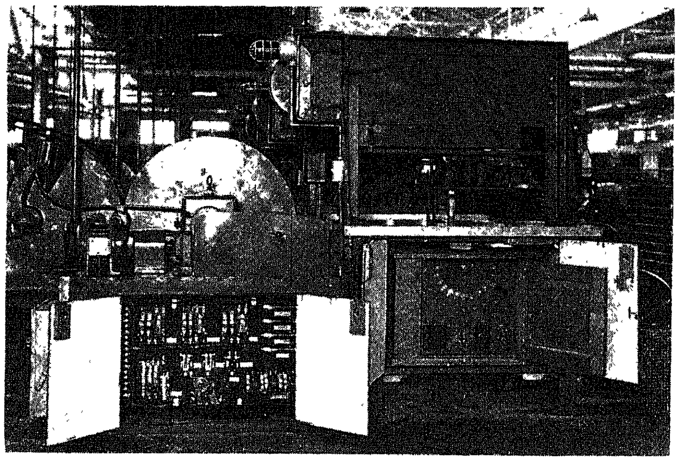

FIG. 5—CONTROL APPARATUS AND MULTI-VOLTAGE TEST BOX

## ECONOMIC FACTORS

The elimination of water testing resulted in several major economies which may be outlined as follows:

1. Reduction in equipment
2. Reduction in floor space
3. Reduction in scrap losses
4. Elimination of process storage

Item 1 is of course of vital importance in the planning of an economical plant, as it affects not only the original expenditure, but also the fixed charges reflected in the operating cost. The saving effected on the original investment represented a reduction of over 60 per cent in the cost of the testing and coiling equipment.

Rental charges applying directly against operating costs were reduced due to the saving represented by item 2, which was reflected not only in the reduced area for testing equipment but also in the elimination of process storage space.

Under the old test method it was necessary to first coil the wire into 1,000 ft. lengths and then water test it, after which the defective coils had to be removed from the water, dried and recoiled to locate the defect. This resulted in the scrapping of a portion of a large percentage of these coils in which the defect occurred near the end, making the short end too short to meet the minimum length requirement of 200 ft. It also necessitated a second operation which was in itself wasteful as it required special recoiling and testing units.

With the new or spark test method the number of short coils which had to be scrapped was greatly reduced, because when a defect occurred it was necessary to cut out only the short section in which the defect occurred and start a new coil. The number of cases where a defect occurred within 200 ft. of the start of a coil was measurably fewer, since no predetermined length had to be maintained.

## FURTHER APPLICATIONS

After successfully applying this test to parallel drop wire, we conducted similar tests on twisted, rubber-insulated and braided wire. The wire in this case was No. 14 hard copper drop wire, which has a 50 per cent heavier insulation than No. 17 BP drop wire, and is comparable in size to No. 14 code wire.

Data were gathered as before, and a satisfactory test voltage established which resulted in the adoption of the spark test for this wire. The voltage was, of course, higher than for the smaller wire, and the success of this experiment indicated the feasibility of spark testing either parallel or twisted wires of various sizes.

It is apparent from the present stage of development of this method of testing that further adaptations are possible which may result in more extensive applications to rubber-covered wires throughout the entire wire industry, with commensurate reductions in the cost of wire manufacture. As previously stated the water test will continue to serve for setting up the proper spark test voltage to insure a sufficient insulation resistance using any particular type of compound, but after this has been determined, using a minimum of equipment, the spark test may be set up to handle the regular production.

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# Discussion

**W. A. Del Mar:** Since the early days of electric wire manufacture it has been customary to give wire a preliminary test by a continuous process. The early apparatus, induction coils operated by direct current and giving a highly unbalanced alternating-current wave of low frequency, was unsatisfactory both because it did not reliably detect weak spots even under the best conditions and because operators sometimes forgot to ground the wire under test. As it became obvious that higher voltages and adequate insurance against open test circuits were necessary, it occurred to me that both of these advantages could be attained by the use of high frequency alternating current. Mr. Lawrence M. Cockaday, then associated with me, designed an apparatus along these lines and it was put to use on an extensive scale in the plants of the company with which we were connected. It was essentially a Tesla coil which gave voltages up to about 20,000 at a frequency of about 200,000 cycles. Somewhat less than half the full voltage was found satisfactory for the ordinary 3/64 in. of rubber insulation and safety to operators was assured by exposing only the high frequency terminals, the remainder of the apparatus being in a closed cabinet.

All wire was tested as it emerged from the tubing machines which applied the rubber insulation to the wire and again after vulcanization as the wire was "depanned" or taken out of the vulcanizing pans. The former test serves to detect faulty application of the insulation or defective stock which is thereupon scrapped. The latter test serves to detect "pinholes" in the insulation which are repaired then and there so that coils of wire of standard length are obtained, which are subsequently tested in water with 60-cycle voltage.

I wish to ask the authors these questions:

1. Do they repair the wire and coil in standard lengths, or do they cut the wire and coil in irregular lengths?

2. Why do they use a frequency of a few hundred cycles when by the use of higher frequencies, shock can be avoided, a spark of greater "searching" ability obtained, and the necessity of grounding the wire avoided?

With regard to the possibility of the spark test superseding the immersion test, the principal difficulty arises from the conditions of inspection by customer representatives. The inspector cannot witness the continuous sparking of thousands of feet of wire. He spends a limited time at the plant and requires a test that can be made in a short time on a large accumulation of manufactured product.

Another objection to the spark test is its unreliability as a detector of flat spots which are much more reliably found by the 60-cycle test in water.

The high frequency sparker as a preliminary testing device is a real help in the production of high quality wire. Its use as the sole test of dielectric strength is in my opinion opening the way to a let-down in quality.

**Robert J. Wiseman:** What is the speed with which the wire travels through the testing outfit? Also, what voltage and time values are used in making the water test? What are the limiting thicknesses of insulation which the authors would consider safe to use on this spark testing method?

**C. W. Protzman:** The answers to Mr. W. A. Del Mar's discussion are given in the following:

1. In our process we cut the wire in irregular lengths. However, repairs could be made if we were required to furnish only standard lengths.

2. As pointed out in our article we tested equivalent quantities of wire manufactured during the same period and under the same process by both the standard test in water and by the spark test, and found that the spark test was slightly superior to the test in water. This was with 60-cycle spark test equipment.

In view of the adequacy of the 60-cycle spark test as demonstrated by our findings as well as some undesirable features of higher frequencies, we did not consider it advisable to design our equipment for high frequencies. Shock is avoided on our machines by provision of suitable guards and automatic interlocking safety devices.

With regard to grounding the wire, it is our belief that this is advisable in order to insure a definite and constant test voltage being applied to the insulation. Means are provided to insure that the wire is grounded during test.

Our manufacturing process with continuous insulating and vulcanizing has greatly reduced the possibility of flat spots. If any flat spots or irregularities occur which would result in an electrical defect these are located by the spark test.

It should be kept in mind that before the spark test voltage is determined for any particular type of wire, a comparative test must be made of the wire with both the standard and spark testing equipment to establish the correct spark test voltage to meet given requirements.

The spark test is inherently a dielectric strength test, and our experience over several years of operation indicates that after the proper voltage is determined as outlined above, wire tested by this method will be of comparable quality to the water tested product.

As previously pointed out, our experience has been entirely with telephone wires, and we are not therefore, in a position to state whether this method of test is directly applicable to other wires.

The following is in answer to Mr. Robert J. Wiseman:

1. The speed of the wire passing through the test unit is 750 feet per minute.

2. The voltage and time values for the water test on No. 17 BP wire are:

| | |
|---|---|
| Breakdown 1,000 volts a-c.............. | time 5 seconds |
| Insulation resistance †500 volts d-c...... | time 1 minute |
| Time of immersion..................... | 12 hours minimum |

†Voltage at 56 deg-64 deg F.

3. The maximum thickness of insulation tested on our equipment is 3/64 in., and the minimum is 1/64 in.

These represent the sizes of wire which we test, but no data are available to define the machine limitations. It is our belief however, that wider ranges are possible.

# Economic Aspects of Water Power

BY F. A. ALLNER*

Member, A.I.E.E.

**Synopsis.**—*This paper gives a brief survey on the economic relationship of hydro and steam power during the past decade, followed by an analysis of typical hydro power costs, divided into the four components; base cost, incremental capacity, transmission, and tie-in facilities. The value of hydro power is analyzed by comparison with the two main components of steam cost, capacity and energy. The possibilities of increasing installed hydro capacity at low incremental cost are emphasized and a method is described of making such low cost capacity furnish firm peak service on the combined hydro-steam load system.*

DURING the past decade, water power in all those regions of the North American continent where it is employed in conjunction with thermal sources of power has undergone a gradual but pronounced change in its economic relationship to steam power. There are two main components that make up the economic value of water power; capacity and energy. The capacity value of hydro plants, or the cost of procuring equivalent capacity service by other sources of power, has not been measurably affected so far by the advance in the art of constructing thermal plants, but the energy value or the cost of producing energy by other means, has been reduced in recent years to the lowest figure ever encountered.

This downward trend in energy value may be traced chiefly to two causes, namely, the improvements in thermal economy and the declining price of fuel, and in a minor way only to miscellaneous causes such as reduction in maintenance cost and operating labor due to improvements in design, concentration of large capacity in comparatively few units, etc. There is some well warranted expectation that the future trend of average fuel prices will be decidedly upward, but probably not sufficient to overbalance materially the effect of further improvements in thermal economy that may be realized in the future.

Since the total energy output for a given water power site is more or less limited by natural conditions of discharge and head, the gain in energy output due to various refinements in the efficiency of energy conversion is necessarily only of minor importance. It is evident, therefore, that the most fruitful field of endeavor for enhancing the economic value of water power will lie in the direction of (a) reducing the investment cost per kilowatt to a point where the carrying charges will compare favorably with equivalent cost of steam power, and (b) increasing the total amount of economically installed capacity beyond the formerly accepted limits and coordinating the operation of the combined sources so that such additional economic hydro capacity can be utilized to render firm peak service to the power supply system of which it is a part.

The purpose of this paper is to review briefly the parallel developments in the economics of water power in respect to these two main components, energy and capacity, and to give an outline of future possibilities for enhancing the economic value of water power.

## FACTORS CONTROLLING CHOICE OF HYDRO OR STEAM AS SOURCE OF SUPPLY

There are few electric systems in this country supplied wholly by hydroelectric generation, chiefly because it has been economically advisable and often necessary to provide low flow reserve generating capacity by means of steam plants located near load centers. There is no generally accepted ratio of hydro to steam capacity for best economic results, but the optimum proportion for any system is determined by the relative investment costs, fuel costs of steam energy, and the characteristics of system load and water supply. Fundamentally, the benefit derived from the two sources of supply comes from the combination of a low operating energy cost in the case of hydro with a low unit investment cost in the case of steam; while the total investment to carry the system peak may be larger in a combined system than with steam alone, the excess investment is more than compensated by the low cost of energy derived from hydro. The two sources of power should be regarded as supplementing rather than competing with each other. The quick starting characteristics of hydro units, namely, the ability to start them from standstill and synchronize them with the load in a small fraction of the time required for steam units, provides a high degree of standby readiness for emergencies. Hydro units, especially of the low head type having short water passages, are well adapted to maintain system frequency. Hydro pondage or storage can be drawn upon to relieve the steam plants of the task of ironing out discrepancies in the forecasting of system load demands, to save banking of extra boilers and generation by less efficient units, and to facilitate the advance scheduling of equipment for generation as well as for withdrawal from service for inspection and maintenance. Hydro generators are also adapted to no-load operation as synchronous condensers for voltage regulation or power factor correction without consuming much energy or requiring elaborate precautions against overheating or rubbing as in the case of steam units.

## FIRM HYDRO CAPACITY

The best method of operation on a combined hydro and steam system is generally found by scheduling the

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*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

hydro plants for maximum efficiency in periods of deficient water, and for maximum energy output in periods of plentiful water. Operation is simplified by the presence of hydro pondage or storage. Hydro capacity is held available during low flow for instant use in case of emergency at associated steam plants. Hydro always supplies a belt on the system load curve according to water availability such that the largest possible hydro capacity is utilized, thereby operating associated steam plants at improved load factors in periods of deficient water.

That portion of the hydro capacity which under certain assumed conditions (generally coincidence of highest system load demands with minimum flow), controlling the capacity investment for the system as the whole, will render the same capacity service in the upper portion of the system load curve which an alternative steam plant might perform, is called "firm hydro capacity." With large pondage and favorable load conditions, the firm capacity of the first hydro plant connected to a load system may be many times the minimum twenty-four hour power available. The minimum flow energy for a second hydro plant, however, feeding into the same load system, will yield a relatively smaller firm capacity than the energy from the first plant, *i. e.*, the increment gain in firm hydro capacity per unit of hydro energy will decrease with an increase in the total amount of hydro energy available.

## Developments During the Past Decade Favoring Water Power

Certain factors of increasing advantage to hydroelectric development have made possible, and hold promise for still greater usefulness of, numerous hydroelectric projects which would not have been considered economically feasible during preceding years, notwithstanding the higher unit value of energy in those years.

Among these factors, is the present large size of electric utility systems in consequence of natural growth as well as of the interconnection of contiguous load areas. Almost without exception, new large scale hydro-developments are made by electric systems which supply their output to metropolitan load centers or to a group of systems covering a regional territory.

The shape of peak of electric system loads is favorable for utilizing a large installed capacity in hydro plant under minimum water conditions, which allows a large capacity value to be allotted to hydro. Especially in the region along the Atlantic seaboard, the sharp peaks of metropolitan load centers, although seasonal and of short duration, may occur simultaneously at the same hour and on the same day. This lack of assured diversity in load demand of interconnected systems, while unfavorable from the point of view of overall power cost, gives pondage equipped hydro plants an opportunity to utilize a greater portion of their installed capacity for firm peak service on the combined load system.

Another feature of large utility system loads has been the annual increase in peak, which has been of such an amount that the entire capacity of new hydro developments has become usable on the peak within a comparatively short time. On the other hand, the minimum system load is sufficient to absorb a large hydro output when water is plentiful in run-of-river plants. Plants which can be developed beyond the continuous flow capacity at a low incremental cost can produce a large volume of low cost secondary energy.

Advance in the art of power transmission has made it possible to transmit large capacities over long distances at reasonable cost, good voltage regulation, and low energy losses. In some instances step-up switching stations at the hydro plants and step-down terminal stations of transmission lines can be developed advantageously as integral parts of interconnection projects, tying together large power systems, which formerly functioned as separate units, into a regional power system extending over large areas. In this manner a dual function is performed by the hydro transmission and tie-in investment, especially on systems which have adopted 230 kv. as standard voltage. The high degree of service reliability of all types of equipment at this voltage has encouraged designing engineers to simplify their system layouts and to rely more on higher mechanical and electrical factors of safety of equipment than a multiplicity of lines and reserve apparatus, all of which had a tendency to reduce investment cost or increase the service value of the hydro projects. Most recent operating experience with high-voltage transmission lines embodying some advanced features of design, has been so satisfactory that lightning proof operation of transmission lines is within the range of possibility at not too distant a future.

At the hydro plant proper, a number of factors have contributed towards the lowering of investment cost, aside from the effect which may be ascribed to lower price levels of structures and machinery. With construction plants laid out for low handling cost and rapid progress, and with careful engineering work applied to temporary structures, flood control, etc., the period of construction has been shortened and substantial amounts are thereby saved which formerly were expended on interest and other carrying charges during construction. Economies in the cost of financing are made possible by the sponsoring or underwriting of major enterprises through existing large utility systems, and few projects are now undertaken for which the market has not been secured in advance at least to the extent necessary to insure the interest on bonded indebtedness with a sizable margin of earnings.

It is possible now to get more capacity out of a given structural space, not only due to increased size of units but also due to higher specific speed of turbine runners and improved design of water passages. Higher speed and improved design of machinery have lowered the cost of main turbine and generator equipment. Auxiliary apparatus has been simplified and its cost decreased.

No appreciable improvement in best efficiency of runners has been recorded during the past decade, at the beginning of which peak efficiencies in excess of 90 per cent had already been reached. However, with the advent of the adjustable blade Kaplan turbine high efficiency can now be secured over a much wider range of loading for low head plants, and the overall efficiency of energy conversion for the plant as a whole has been raised noticeably over that of earlier installations. Testing of models is no longer confined to runners and draft tubes, to observations of efficiency, output, and to studies of the cavitation problem, but extends to every phase of the project from headwater down to the lower end of the tailrace channel. As a result of model tests, more economic designs of spillways, pier and apron sections, flood gates, etc., have been developed. Effective steps have been taken at the newer plants to guard against service interference by trash and ice runs.

## PUMPED STORAGE PLANTS

Pumped storage plants involving specially constructed high- or low-level storage reservoirs, do not play so important a part in the power supply scheme of large systems as they do in continental Europe. Several such projects are under discussion, but only one major installation, a plant built in 1928 on the Rocky River, a small tributary of the Housatonic River, in New England, is actually in service. The plant pumps from the Housatonic River to a reservoir of 68,000 sec-ft-days usable capacity located on the Rocky River. The average yearly runoff of the Rocky River is 17,000 sec-ft-days.

While pumping is done mainly by off-peak steam power, the Rocky River plant provides in addition seasonal storage service to other plants located below on the Housatonic River. The installation of the 24,000-kw. generating unit in the Rocky River plant and the pumped storage reservoir actually added 40,000 kw. of yearly firm capacity to the electric system served by the plant. The efficiency of direct recovery by the Rocky River plant alone is approximately 60 per cent, but on account of the presence of the lower plants the overall conversion economy derived from all plants is raised to nearly 80 per cent.

## DUAL USE CAPACITY INSTALLATIONS

This novel type of development is functionally related to pumped storage plants, being based on the principle of converting low cost off-peak energy into high value peak capacity and energy. It employs the same unit as a turbine-generator and a motor-pump set, without however requiring a specially constructed high- or low-level storage reservoir, conduits or hydraulic control equipment. It is especially adapted to those hydro plants where the increment cost of generating and transmitting capacity is lower than that of equivalent steam capacity and where a substantial overlapping of heads can be readily arranged. The runoff characteristics should be such that, depending on the efficiency of the conversion cycle, the duration of the low-flow stage, during which conversion of off-peak energy into peak energy takes place, is not too great compared with the duration of the excess flow period, during which the dual use equipment produces energy for the system. The above conditions are somewhat interrelated in that in some instances a large saving in investment cost may more than compensate for the extra cost of energy caused by conversion losses during low flow exceeding the gain in output during high flow, notwithstanding the fact that on such a project the low-flow days may greatly outnumber the high-flow days.

The operation of the generator in reverse direction as a motor offers no serious difficulties but the design of the different types of turbines and hydraulic structures for dual use at synchronous speed and the possibilities of variable speed electrical and hydraulic equipment have not yet been developed to such a degree that this simplified regenerative cycle can be readily adapted to those hydro projects where natural conditions of the power site are favorable.

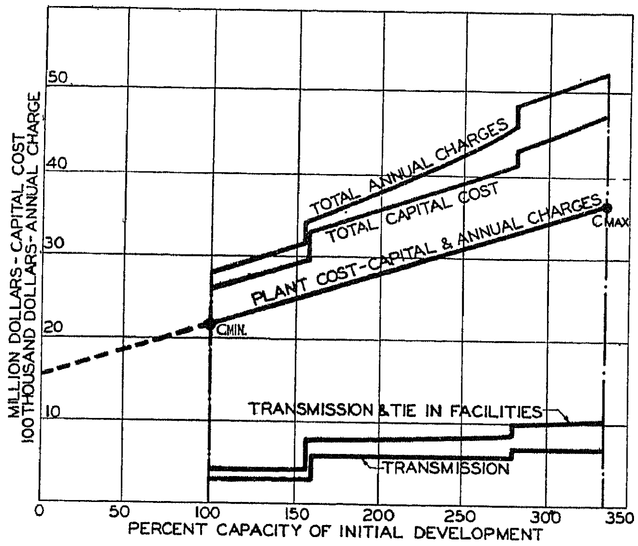

FIG. 1—ANALYSIS OF COST OF HYDRO PROJECT

A great deal has been published in the technical literature, especially in Europe, on the principles and applications of pumped storage predicated in each instance on the employment of two separate hydraulic motors, one for generation and the other for pumping, and in nearly all cases also on the presence of a specially constructed high- or low-level reservoir. The employment of a single hydraulic motor for dual function and the omission of specially constructed reservoirs introduce substantial economies in capital investment, but involve a sacrifice in efficiency of conversion.

Perhaps in the search for the optimum of efficiency, we are inclined at times to throw aside as unworthy of further study, the suggestion that a process which is admittedly inferior from a point of view of efficiency may yet be superior from the point of view of overall economy.

The simplified method of hydro regeneration has not been treated so far in the technical literature. As a proper evaluation of the possibilities of this process is of some importance on account of its effect on the economics of future hydro developments, the principles underlying this method as well as certain empirical results from laboratory and field tests are described in greater detail in an Appendix, including an analysis of those factors that will limit its field of application.

## ANALYSIS OF HYDRO POWER COSTS

There are four main components that may properly be regarded as the cost of hydro power, namely:

a. Base cost of the development, which is more or less independent of the amount of installed generating capacity.

b. Cost of generating capacity, including low-tension switching equipment.

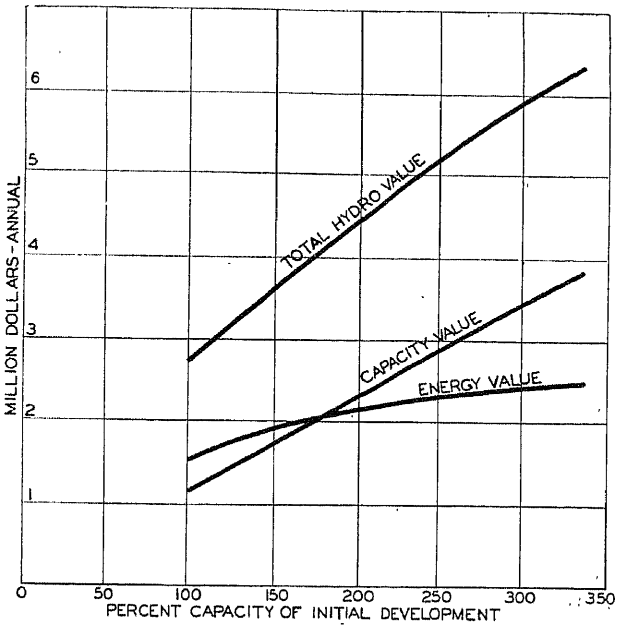

FIG. 2—ANALYSIS OF VALUE OF HYDRO PROJECT

c. Transmission investment, including step-up transformers and other high-tension equipment at the power house.

d. Tie-in investment, such as step-down transformer and switching stations, underground cables, and other special equipment necessary for delivering hydro power to a distribution system or to a high-tension network.

Until quite recently it had been customary to group the first two components into a single item, "cost of power plant." This practise was usually adequate for the purpose when investigating the economics of existing plants. However, segregation into the two components,—base cost and increment cost, is almost indispensable during the preliminary or project stage of a new development in order to determine the most economic size of the initial and ultimate installation and the part that it should play in the power supply scheme of a territory. The fact that such a differentiation exists, that the two components can readily be segregated and that their relative magnitude as well as their value per unit of capacity furnish a yardstick for comparing one project with another, is one of the characteristic economic features of hydro plants as distinguished from steam plants, where the first component, base cost, ceases to be an important factor after more than one generating unit is installed.

Cost of dam, property, flowage rights, construction equipment and temporary structures, relocation of bridges, highways, railroads, general site improvements, a certain minimum of tailrace excavation, auxiliary station equipment, etc., all of which are more or less independent of the amount of capacity installed, constitute Base Cost. Due to a great variety of causes this cost for almost identical hydraulic conditions of head, average discharge and length of backwater, may show variations of several hundred per cent.

The second component comprises the cost of generating equipment, hydraulic as well as electrical, power house substructure and superstructure, low-tension switching and auxiliary equipment, intakes, control equipment, increment tailrace excavation, etc. It is sometimes called the incremental cost of hydro capacity. For similar hydraulic conditions this second component, expressed in dollars per kilowatt, is almost constant, except for major fluctuations in price levels and for differences in the accessibility of the power site. Even over a wide range of hydraulic conditions it will rarely deviate more than 25 per cent from the average, which is approximately $60 per kilowatt.

Considering the approximate constancy of incremental cost and the great variation of base cost, a full answer to the question whether a hydro plant is a high- or low-cost development, cannot be given unless total power plant costs are segregated into these two components. For purposes of illustration, the values used in Fig. 1 and Fig. 2 have been selected as a representative average for a low-head pondage equipped run-of-river plant, located on the Eastern slope of the Appalachian range.

During the project stage, when only estimated and not actual cost figures are available, this approximate division of cost may be obtained by plotting against kilowatts of installed capacity as abscissa the estimated cost for the minimum capacity (C min.) as well as for the maximum capacity (C max.) that is under consideration. The point of intersection of a straight line, drawn through these two points, with the axis of cost will give the approximate value of the base cost component. As certain structural provisions must usually be made initially to permit expansion to a larger ultimate capacity the actual cost of the minimum capacity installation (C min.) will be somewhat higher than the estimated cost of minimum capacity exclusive of these provisions for future expansion.

The vertical scale in Fig. 1, representing capital cost, can be converted readily into a proportionate scale of annual charges, as the sum total of interest charges, taxes, depreciation, operation, maintenance and other expenses is approximately proportionate to investment. In Fig. 1 the overall rate has been assumed at 10 per cent, based on an average return of approximately 7 per cent on investment. Depending on the method of financing, this overall rate may be somewhat reduced especially during the initial years.

The sum of the first two components represents the cost of the power plant proper, controlled largely by the hydraulic characteristics of head and discharge and by local conditions at the power house site and along the shores of the pond or reservoir. The other two components of cost, transmission and tie-in investments, are controlled by the geographic location of the plant in respect to its potential market and by the opportunities of effecting a physical tie-in to existing lines of distribution networks at a minimum of cost.

Although bearing hardly any relation to plant costs, yet these two components must be fully considered as cost elements for hydro power. It is not infrequent that a low-cost and in every other way seemingly ideal project is uneconomic by reason of excessive transmission and tie-in cost. Conversely, certain other projects may be favored by short transmission distances to load centers, nearness of existing high tension lines, advantageous location of step-down stations in respect to city distribution systems, etc.

In some special cases these two components of costs may become a credit rather than a charge. If, for example, a large power consuming industry is located so close to the power site that it can be economically served at generating bus voltage, there will be a saving in transmission cost compared with supplying power to that industry from a more distant source; or if nearby railroad lines which often follow the course of rivers, are electrified, there may be a distinct saving in tie-in expense not only by reason of the nearness of the electrified tracks but also, in the case of the 25-cycle single-phase system, by reason of employing at the lower speed single-phase hydro generators instead of the customary frequency converting equipment required in connection with 60-cycle steam power.

The above described cases are exceptional rather than average conditions. As a rule, the combined cost of transmission and tie-in investment will appear in the nature of a charge rather than a credit for hydro power. Especially where long distances are involved, such as Boulder Dam or the St. Lawrence Development, the cost of these two components may be equal to or exceed the increment cost per kilowatt of installed hydro capacity. The development of 230-kv. transmission had a tendency, where large amounts of power are involved, to reduce the transmission cost per kilowatt for a given distance, but to increase slightly the tie-in cost.

As extensions are made at the hydro plant the cost of transmission will increase in sharp steps corresponding to the building of additional transmission lines, but the tie-in costs will usually grow at a gradual rate, corresponding to the step by step installation of additional underground cables and other tie-in equipment to keep pace with the increase in hydro capacity.

The annual charges in connection with transmission and tie-in facilities will bear again a proportionate relation to the investment, but at a somewhat higher rate (12 per cent to 15 per cent) than that used for the annual charges of the hydro plant proper.

While it may appear academic to combine at an early stage of the project the estimated cost of the hydro plant proper with the cost of transmission and tie-in facilities which are indirectly dependent upon the marketing of hydro power, yet a tentative forecast of these cost components is indispensable for a preliminary investigation of the economic justification of a project. Instead of adding these two components to the other costs of hydro power, one could subtract these items from the composite value of hydro power, which is analyzed in the section below. This latter method, however, would not give as clear and convenient a graphic picture of the relationship of overall cost and value.

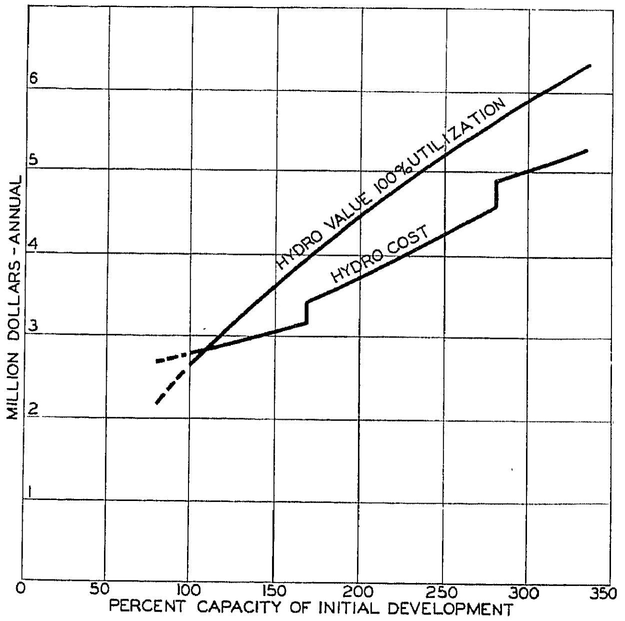

FIG. 3—COMPARISON OF HYDRO COSTS AND VALUE

## VALUE OF HYDRO POWER

The generally accepted yardstick for evaluating hydro power is to determine the replacement cost of its two main components, capacity and energy, by the cheapest alternative source of supply, namely steam. Hydro projects that are so situated that they have only a single potential market for their output, are more readily analyzed than those projects which have several possible outlets for power and the operation of which can be so coordinated with the operation of the several steam plants that hydro power renders the relatively most useful, and therefore the most valuable service to the combined system.

Aside from the replacement value of hydro power as measured by the steam yardstick, a hydro plant, especially if located upstream in respect to a series of individual plants on the same river or watershed, may, by proper coordination of power house discharge, add materially to the energy and capacity output of the plants located downstream. There are also a number of other more or less collateral or contingent advantages of hydro power which it would be difficult to express in definite figures. Some of these features have been referred to in a previous section, dealing with the choice of hydro or steam as a source of supply. For the purpose of this approximate analysis, however, all these collateral features are omitted and evaluation of hydro is confined to the two main components of capacity and energy

It is evident that only that amount of installed capacity can be credited to hydro at the cost of equivalent steam investment which renders a corresponding amount of firm peak service on a given system load, and which would otherwise have to be provided in the form of steam investment in order to insure adequate reserve capacity for the system. This definition would, strictly speaking, limit in the initial year the capacity value of a hydro plant of any type to the annual increase in connected system load, or at the most, to the capacity of a single steam unit, if the latter is larger than the anticipated increase in system load. This rather narrow definition is gradually giving way to the long range point of view, taking into account the average capacity value rendered over an extended period.

For a given amount of minimum flow energy, the amount of hydro capacity that can render firm peak service to a system will gradually increase with the growth of system load, provided the load at least in the upper portion of the curve retains approximately the same shape. If additional load areas which heretofore supplied all their requirements by steam, can be tied in to the new hydro plant, the firm peak service rendered to the combined system will be materially increased, provided, of course, that the character of these new load areas is similar as to shape of load curve as those originally served by the hydro plant, or possibly still more favorable for the utilization of firm peak service by reason of pronounced seasonal peaks.

The capacity value per kilowatt comprises, in addition to the fixed charges, *i. e.*, interest, depreciation, taxes, insurance and some general expense, also those items of steam plant operating costs which are more or less independent of the amount of generation. This combined value varies somewhat in different localities. Aside from differences in price levels, it is probably more affected by the size of individual steam units than by any other single factor. Under present day conditions its lowest value is perhaps in the neighborhood of $10.00 per kilowatt and in some instances exceeds $18.00 per kilowatt for medium size, but otherwise modern stations, the average being in the neighborhood of $13.00 which is the value used in Fig. 2.

The energy value per kilowatt-hour comprises, in addition to the cost of fuel and maintenance, only some minor items of operating supplies and labor. Depending mainly upon the price of fuel in the territory, the heat cycle of the station and the relative size of boiler and turbine units, the energy value under present day conditions may be assumed to vary, except in the case of mine mouth plants, from a minimum of around 2.0 mills per kilowatt-hour or slightly less, to a maximum of around 3.0 mills, the average being perhaps 2.5 mills for unit capacities of 50,000 kw. or higher.

This latter value has been used for computing the total energy value of the hydro project analyzed in Fig. 1 and Fig. 2, assuming full utilization of the hydro energy available.

In order to approximate the effect of transmission losses, of capacity reductions by flood stages, drawdown of pond, etc., certain percentage reductions have been applied to energy as well as capacity. For less than 100 per cent utilization of either installed capacity or available hydro energy, the combined curve will drop below the values indicated, the amount of which reduction can be readily determined as a proportionate reduction of the respective component parts.

The composite curves of hydro costs and hydro values have been replotted in Fig. 3 in order to bring out more clearly certain trends frequently observed in connection with major hydro projects serving a large interconnected load system supplied by hydro and steam. During the initial years of operation, hydro will compare less favorably with steam values than during later years. However, there is a reasonable expectation that a hydro plant which has low incremental cost and not unduly high cost of transmission and tie-in facilities will in the long run yield a substantial margin of savings below the cost of steam. In addition, there will be a number of collateral advantages to its credit, which have been omitted in the above graphic presentation.

## Appendix

### REGENERATIVE CYCLE AT PONDAGE EQUIPPED HYDRO PLANTS

### SECTION I

The practise of storing water by pumping into specially constructed reservoirs for the purpose of producing peak power, started over thirty years ago. Compared with electric storage batteries or the storage of energy in heat or pressure accumulators, the pumped storage of water shows greater flexibility and is more economical per unit of stored energy, although the efficiency of conversion is lower than that of other means of storing energy.

The maximum overall efficiency of a pumped storage plant in which each element is designed to do its respective duty in the most efficient manner is approximately 65 per cent, obtained as follows:

| | Per cent efficiency |
|---|---|
| (a) Transmission from thermal plant to low tension bus of hydro plant | 96 |
| (b) Driving motor at unity power factor | 97 |
| (c) Average pump efficiency | 85 |
| (d) Slope of pond, head loss through racks etc., when pumping | 98 |
| (e) Slope of pond, head loss through racks etc., when generating | 99 |
| (f) Turbine | 90 |
| (g) Generator | 96 |
| (h) Transmission from hydro plant to low tension bus of thermal plants | 96 |
| Product of all efficiencies (a) to (h) | 63.7 |
| Product of all efficiencies (b) to (g) | 69.0 |

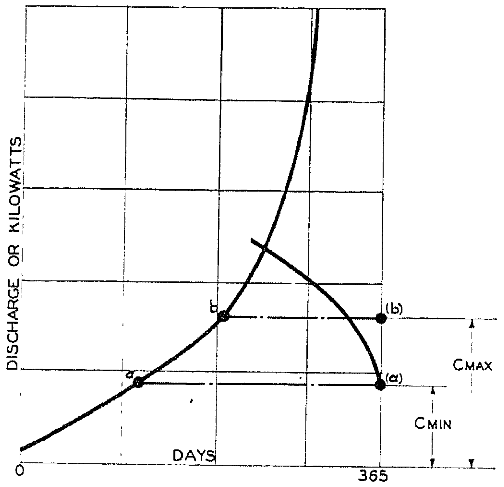

Fig. 4—Flow Duration Curve

Pumping efficiencies of approximately 60 per cent can be obtained by operating in reverse direction, but at the same speed and head, certain types of turbine runners which were originally designed to function only as water wheels.

Substituting in the above tabulation the efficiency of 60 per cent for the high average efficiency of the specially designed pump (85 per cent), the above overall efficiency of conversion of 63.7 per cent is reduced to 45.0 per cent.

As the three-phase generator can be readily adapted for reverse operation as motor merely by the interchange of two armature leads, the dual use of turbine runner and generator as motor-driven pump will entail only a negligible amount of investment to accomplish the purpose of regeneration. If operating conditions are such that the regenerative cycle must normally be repeated every day, the lowering of the overall conversion efficiency will amount to an appreciable sum in an average year, probably sufficient in many instances to overbalance the possible saving in investment.

However, at pondage equipped run-of-river plants, that have a pronounced low-flow stage, corresponding approximately to the flow duration curve shown in Fig. 4, the number of days on which operation under the regenerative cycle is necessary will be relatively small and the loss of efficiency due to the use of the turbine unit as a pump instead of a specially designed pumping unit will not be such an important factor.

Necessity for the regenerative cycle will arise probably only in the event of coincidence of heavy load demands, minimum flow, and outage of steam reserves on the load system served by the hydro plants. The increased energy consumption due to the lowered efficiency need not be viewed therefore as a continual operating expense, but it will be of the utmost importance to establish beyond doubt that the dual use equipment can perform the full duty expected of it for the purpose of firming a certain amount of installed hydro capacity. This phase of the problem is dealt with in Section II. The purpose of the present investigation is to determine for a typical example the approximate amount of additional hydro capacity that may be installed at low increment cost in excess of that capacity which is rendered firm on the system load by the minimum natural inflow.

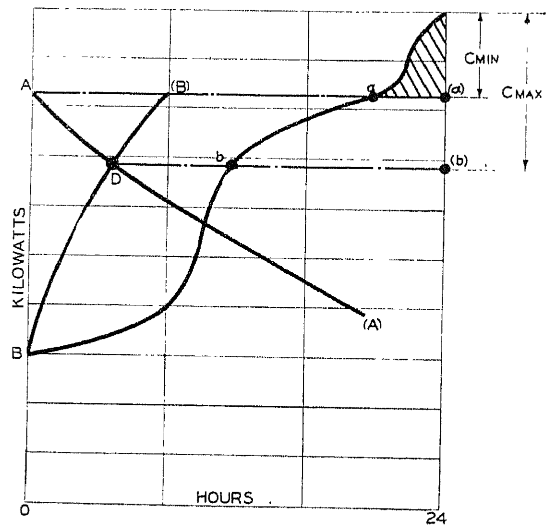

Fig. 5—Load Duration Curve

The load duration curve for a typical heavy day in Fig. 5 is assumed to be normally supplied by a combined hydro-steam system of which hydro furnishes at times of minimum regulated river flow the cross-hatched upper portion of the load area. C min. represents the corresponding amount of hydro capacity rendering firm peak service to this load system. The area to the left of the curve will be called the no-load area.

The integrated load area below the horizontal line *a*(*a*) is plotted at a suitable scale as a curve starting at point *A* in such a manner that the abscissa of any point along the curve *A*(*A*) represents the load area lying above a horizontal line through that point and below line *a*(*a*). From point *B*, which corresponds to the minimum load of the load duration curve we plot now a curve $B(B)$, any abscissa of which represents the integration of the no-load area below a horizontal line through the selected point multiplied by the overall efficiency of conversion. A horizontal line drawn through the point of intersection $D$ of these two curves will divide the load curve into an upper area that can be supplied by hydro produced by natural inflow as well as by regenerative cycle, and into a lower area in which the steam plants will operate at 100 per cent load factor.

The assumption has been made in the above that the regenerative cycle is not limited by the capacity of the upper or lower pond or by excessive variations in operating head. It is also apparent that the installed hydro capacity is approximately equal to the full amount of off-peak steam capacity available. A somewhat larger amount of hydro capacity may be installed and render firm peak service if the load system is interconnected with other steam plants that have a large amount of off-peak steam energy available during the pumping hours.

Increasing the installed capacity from C min. to C max. will yield a certain amount of additional high-flow energy as indicated by the area $a(a)$ $(b)b$ in Fig. 4. It will be of interest to compare this gain in high-flow energy in an average year with the energy consumed as conversion loss in the regenerative cycle. Instead of integrating the load areas lying between two capacity lines, we can more conveniently compare the increment gain in output per kilowatt for any value of installed capacity with the increment loss corresponding to that capacity. The horizontal distance of the duration curve in Fig. 4 from the 365 day ordinate gives the number of days on which a certain amount of capacity will still be able to turn out full output for 24 hours. Thus the number of days represented by the horizontal intercept to the right of the curve, multiplied by 24 hours will give the energy yield per kilowatt at that value of installed capacity. An incremental loss curve will now be added in which horizontal intercepts also express the energy loss per kilowatt at various values of installed capacity.

The energy consumed for conversion losses is zero at the point C min. and is plotted on the 365 day ordinate. The increment conversion losses of a single day corresponding to an installed and firmed capacity of C max. will be equal to the distance $(b)b$ indicated in the load duration curve of Fig. 5, multiplied by the coefficient $\frac{(1.0\text{—conv. eff.})}{\text{conv. eff.}}$. The number of days on which such increment conversion loss is incurred can be determined from the flow duration curve of Fig. 4 by converting the whole load area supplied in Fig. 5 by the hydro capacity C max. into 24-hour load at 100 per cent load factor, entering this average load on the duration curve in Fig. 4 and reading the number of days of deficiency at that point. This number of deficiency days is computed to the same scale as the duration curve by multiplying by the incremental loss divided by 24 and is plotted to the left from the 365 day ordinate. The point of intersection of the flow duration curve with the incremental loss curve will indicate the amount of capacity installation beyond which the high-flow energy gains will be exceeded by the conversion losses in an average river year, assuming, of course, that during the entire period of low-flow, firm peak service to the extent of installed hydro capacity must be produced by the combined effect of natural inflow and regenerative cycle and without any assistance whatever from steam reserves.

## SECTION II

One of the best known examples of converting pressure into velocity and back again into pressure is the Venturi meter. Its overall efficiency of conversion is very high. Care is taken in the design so that the flowing water is accelerated and retarded with an almost negligible loss of energy. Such ideal conditions can, of course, not be duplicated in a water wheel with its serial arrangement of stationary and rotating water passages involving sharp changes in velocity and direction of flow. Under those conditions efficiencies in excess of 90 per cent are quite an achievement. A high rate of acceleration is possible without disturbing the continuity of flow which permits a compact design, short water passages, and a minimum of wetted surface and friction. Retardation of water, *i. e.*, conversion of velocity into head, cannot be accomplished at as high a rate as acceleration without disturbing continuity of flow, which causes turbulence and shock losses. Energy conversion in a centrifugal pump, therefore, cannot be carried out at as high a rate of efficiency as in the turbine, because water passages must be designed for a more gradual rate of diffusion, which will require a

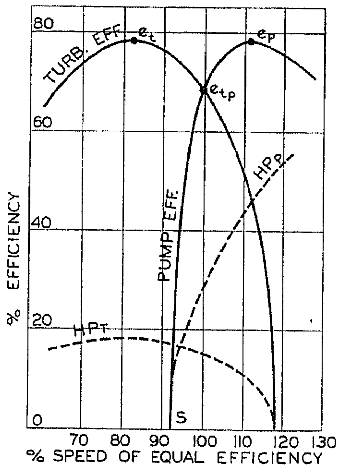

FIG. 6—TURBINE PUMP CHARACTERISTICS

Single-phase centrifugal pump

larger amount of wetted surface and greater friction loss. The best efficiencies ever reached by centrifugal pumps are between 85 and 89 per cent. Although apparently only 5 per cent less than best turbine efficiencies, yet, this difference in terms of losses means that the best pump has from 50 to 75 per cent greater losses than the best turbine.

A centrifugal pump that has its best efficiency under certain conditions of head, speed and discharge for which it is designed, can be made to function as a turbine at the same head and will show the same efficiency, though at reduced speed and discharge. Fig. 6 shows the characteristic curves obtained from tests on a single, stage, 125-hp. circulating pump. The efficiency curves intersect at a point approximately 10 per cent below that of best efficiency. For an installation where the hours of pumping and of generation are approximately equal, synchronous speed of normal operation for this type of runner should be in the vicinity of this point of intersection. There is a certain risk, however, in lowering the operating speed materially below that at which the runner has best pump efficiency, because with only a few per cent further reduction in speed, (or an equivalent increase in head), the efficiency will drop off rapidly and the runner will stop pumping altogether. In the example shown in Fig. 6, this latter point, usually called "speed of impending delivery," lies only about 7 per cent below the speed of equal efficiency.

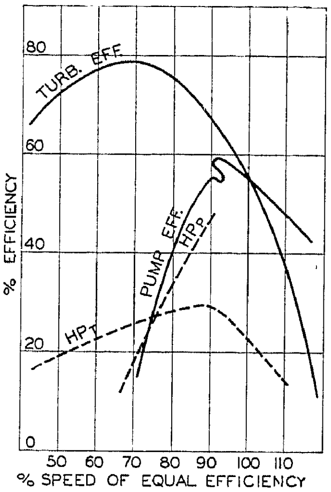

Fig. 7—Turbine Pump Characteristics

Francis turbine

Another drawback of employing this type of runner for dual use is indicated by the relation of horsepower input for pumping to horsepower output for generation. At best, a runner of the characteristics as found in Fig. 6 may be considered for dual use operation only under certain special conditions where the hours of pumping under average conditions will greatly exceed the hours of generation. For example, at some of the existing seasonal pumped storage plants, a motor pump set may be used as a generator at from 25 to 50 per cent of its rated motor input, and at an efficiency of around 50 per cent on some rare occasions of sharp seasonal peaks of short duration. It will contribute whatever turbine output it is capable of, as so much additional firm peak capacity to the system at practically no additional cost.

That the modern type Francis runner with its short and sharply reduced and warped water passages is not well suited for regenerative operation, is illustrated in the characteristic curves of such a runner shown in Fig. 7. While the maximum efficiency of this turbine runner appears no higher than that of the centrifugal pump shown in Fig. 6, it should be borne in mind that Fig. 7 gives the test results on a small model, whereas the values of Fig. 6 were obtained from a full size installation. Normal synchronous speed of a modern high-specific-speed Francis runner lies usually in a range somewhat below the speed of impending delivery when operating the same runner as a pump against the same head. Except in some rare cases, where an abnormally large overlap of head between serial plants on the same river permits large fluctuations in operating head, or at storage reservoirs having an unusually large drawdown, this type of runner cannot be employed for pumping at synchronous speed. However, if coupled with either dual or variable-speed generators, the modern Francis runner has some distinct possibilities for regeneration.

The tests on this type of runner covered a wide range of conditions as to speed, head, gate opening, etc., in combination with three types of draft tubes; elbow, spiral and straight conical. Some of these test results are shown in Figs. 8 and 9. There was a considerable spread in the speed of impending delivery, as well as in the speed of best pump efficiency for the different types of draft tubes. With the elbow tube, the runner commences to pump at a much lower speed than with the conical tube. The maximum pumping efficiency with the elbow tube was several per cent lower than with the other types of tubes, but at a lower range of speed. Reduced gate openings have the effect of materially lowering the speed of impending delivery for all types of draft tubes.

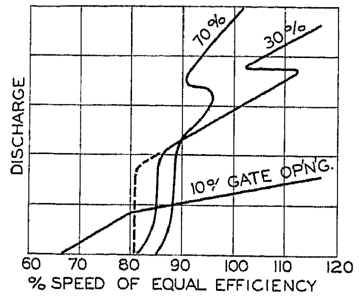

Fig. 8—Speed of Impending Delivery

Various gate openings—Francis turbine

There is some reasonable expectation that the Francis type of runner can eventually be developed for dual use at synchronous speed, especially at medium head installations, if certain modifications are made in the design, without appreciably increasing the cost of equipment or lowering the turbine efficiency. One of these requirements is that peripheral velocity be raised slightly above the $\sqrt{2\,gh}$ value corresponding to the highest expected pumping head; changes in cross-sectional area of water passages have to be more gradual, the design then leaning towards a fewer number of, but longer blades; such runners will probably be designed for lower specific speed, the ratio of axial length to diameter more nearly approaching that of the older type of Francis runners.

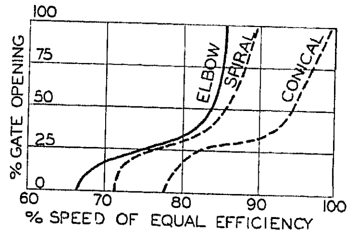

FIG. 9—SPEED OF IMPENDING DELIVERY

Different draft tubes—Francis turbine

Among the various types of turbine and pump rotors which are now available and which are designed primarily for a single function, *i. e.*, either generation or pumping, the propeller turbine, and especially the Kaplan adjustable blade type, seem to offer the greatest flexibility for dual use in the regenerative cycle.

Fig. 9 shows the efficiency curves of a 16-inch model over a range of 60 to 130 per cent of rated turbine head. Over this whole range of operation, the efficiency of the model drops only slightly below 60 per cent, the maximum being 65 per cent. The test results were obtained in the low-head laboratory. Although these efficiencies checked very closely with the test results in the high-head laboratory, certain practical limitations were set by cavitation. At operating heads below 50 feet this will probably not be a serious drawback, especially if serial plants on the same river are laid out with a substantial overlap of head.

## SECTION III

Certain features influencing the extent to which hydro regeneration will be economic have been referred to in the preceding sections as follows:

Relation of deficiencies in flow to duration of high-flow stages.

Amount of pumping power and number of pumping hours during each cycle.

Efficiency of regenerative conversion.

Overlap of head and cavitation limit.

Relation of increment cost of additional hydro capacity including transmission and tie-in investment, to increment cost of steam capacity.

Aside from the above considerations, any one of which may control the upper limit at which regeneration ceases to be profitable, there is one additional factor that will in many instances set a definite limit on the regenerative cycle, namely, the amount of pondage available.

The ideal condition would be the presence of two large lakes, which contain in the first foot or so of storage such a large volume that many times the minimum natural inflow can be shifted every day from the upper to the lower level and back again without any appreciable drawdown in the upper, or rise in the lower level. This ideal condition would be rarely encountered, and usually there will be an inequality in the two ponds, the smaller one of which will of course establish the limit for the regenerative cycle. As this question of pond limitation is of some importance, an approximate formula will be developed for the purpose of establishing a relationship of the energy obtainable by pondage under drawdown conditions to the theoretical energy obtainable by the same amount of water if both ponds were of unlimited capacity.

The water discharged into the lower pond in excess of the natural inflow will cause a lowering of the water level in the upper pond and a rise in the lower pond. The drop in the upper plus the rise in the lower pond represents the reduction in head, under which the upper plant will operate at the end of the drawdown period. The lower plant will operate during the whole drawdown period at a gradually increasing head, the maximum at the end of the drawdown period being equal to normal operating head plus the maximum rise in the lower pond. Thus, there will be on the average a lowering in the combined effective operating head of the two plants, *i. e.*, a reduction in output from natural inflow

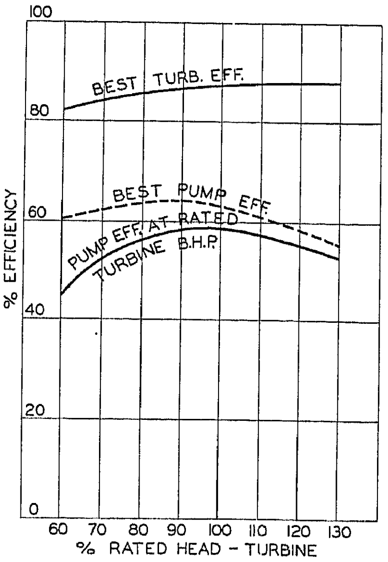

FIG. 10—TURBINE PUMP CHARACTERISTICS

Adjustable blade propeller turbine (Kaplan) alone, below that obtainable from the same water under normal head conditions.

Assuming that there will be no physical limitations, other than those controlled by practical operating conditions, along the shores of the lower pool (railroads, highways, buildings, etc.), or at the power house structure itself, we may expect that the excess drawdown may be carried to a point, where either an excessive lowering of head renders turbine operation at the upper plant too inefficient or impractical or where the increased capacity at the lower plant would overload the generators. The limit will probably be first reached at the upper plant and approximately at that head which is the capacity controlling one at times of very high flood stages.

This maximum reduction of head has been assumed at approximately 40 per cent. Instead of expressing pondage, useful for regeneration, in absolute terms of million cubic feet or in cubic feet per second average flow during 24 hours, it will be expressed in relation to minimum natural inflow, calling the ratio between the two $(X)$, which ratio will be shown to have a bearing on the net gain of energy that can be secured over a wide range of pond ratios, *i. e.*, relation of upper pond area to lower pond area.

This net gain $N$ in kilowatt-hours is independent of the head at the lower plant. It may be expressed in the following general equation:

$$N = f_n h_1 \left[ (X) - \frac{(X)(Y)}{2} - \frac{(Y)}{2} \right] + f_n \frac{d_2}{2}$$

in which:

$f_n$ = kilowatt-hour during 24 hours of minimum natural inflow at one foot head.
$h_1$ = normal head at upper plant.
$f_n h_1$ = kilowatt-hour during 24 hours of minimum natural inflow at normal head of upper plant.
$(X)$ = ratio of usable pondage to natural inflow.
$(Y)$ = ratio of upper level drawdown $d_1$ plus lower level rise $d_2$ to normal head at upper plant.
$d_2$ = maximum rise at lower pond.

For a maximum practical $(Y)$ of 40 per cent and different ratios of $(X)$ from 1 to 5 and three assumed pond ratios (unlimited upper pond, both ponds of same characteristics, lower pond unlimited), this equation will lead to the following coefficients of net gain, *i. e.*, relation of kilowatt-hour obtainable by pondage under drawdown conditions to kilowatt-hour obtainable by the same amount of water if both ponds were of unlimited capacity:

| (X) = | 1 | 2 | 5 |
|---|---|---|---|
| | Per cent | Per cent | Per cent |
| Unlimited upper pond | 80 | 80 | 80 |
| Upper and lower pond identical | 70 | 75 | 78 |
| Unlimited lower pond | 60 | 70 | 76 |

## Discussion

**Alex. E. Bauhan:** It is refreshing to see a paper treating the relative economies of water and steam power in such a thoroughly sound manner. It is quite a contrast with some misleading presentations which have been made in the past in which the comparison is made in mills per kwhr, perhaps with some qualifying discussion as to load factor. As in the case of many other problems, comparison of the total annual costs of one plan and of the other must be made before sound conclusions can be drawn.

There are two thoughts presented here, neither of which is a criticism of the paper and both of which I appreciate Mr. Allner is cognizant of, and which he probably felt were beyond the scope of his paper. However, the writer thinks they are worthy of at least mention in order to avoid misapplication of the paper.

The first thought deals with the determination of energy value. This is taken as the incremental energy cost in the competing steam plant and is mentioned by Mr. Allner as averaging about two and one-half mills per kwhr. In determining this value it is not sufficient to take the energy which will be generated by the hydro plant, or the increment of hydro capacity which is under consideration, and multiply it by two and one-half mills. If the competing steam plant is able to generate a larger amount of energy than the hydro capacity, and this is usually the case, especially if one of the later increments of hydro capacity is being considered, this additional energy redounds to the credit of the steam plant to the extent that its incremental cost is less than the incremental cost in the existing steam plants which otherwise would have generated this energy. For instance, consider an increment of firm hydro capacity of one kilowatt which is usable 3,000 hours per year. The use of the competing one-kilowatt of steam plant capacity is perhaps 7,000 hours per year. The excess is 4,000 kwhr, and would be used to relieve generation on older higher cost marginal stations to that extent. If the saving in production expense resulting therefrom is one mill per kwhr, the steam plant receives a credit of $4.00 per kw-year, which of course correspondingly diminishes the value of the hydro installation.

The other thought is that although curves plotted on the basis of per cent capacity installed, such as used in this paper, may show a hydro cost, after the initial development, materially below the hydro value, one must not draw the conclusion that the project is economically justified. The dimension of time enters. One must go a step further and plot hydro costs and hydro value against years. Such a comparison may show that the initial hydro development, especially if it is large in comparison with the annual load growth, has a value less than its cost for a number of years. This loss accumulates with compound interest and unless the profits from future years' operations are marked, it may never be made up. In other words, the project is not economically justified.

The introduction of the time element brings with it the uncertainties of future loads and future competitive plant costs. Those uncertainties make the ultimate decision largely a matter of judgment in which, it may be said, the economic analysis is an indispensable aid.

**William McClellan:** Those who, like the writer, have been examining eastern water powers for a great many years will know the progress that has been made and what a vast difference there is in the economic use of water power by and large in the eastern part of the United States where the heads are low compared with the water powers in the mountainous regions in the West. At the beginning we knew no better than to treat those water powers as entities in themselves and we were confronted in most cases with low heads and greatly varying flows. The problem was difficult because the head was not only very variable owing to low water, but also at flood times. Equipment such as discussed in the paper had not yet been designed. A project was regarded as a prime source of power with or without a certain measure of steam reserve. Our only superficial measure of its value was the price per horsepower required for the total development. Later transmission came by which we were enabled, not only to put the power into more distant markets, but also to make the power a part of existing large systems which could be regarded either as sinks for all the kilowatt hours we could develop or, as Mr. Allner has pointed out, some of the powers could be used as power storage devices for lifting off peaks in steam systems and other purposes.

Mr. Allner's paper brings out that a proper point of view is the *sine qua non* in approaching any problem of this sort which has any economic complexity. In brief, this proper point of view is not that of the water power as an entity in itself, but as one of the features in the power supply for a given district or region. When the problem is approached from this standpoint, as has been pointed out, we have the possibility of developing an installed capacity far beyond anything we would have dreamed of in past years. True, it becomes a very nice point for decision, based upon extremely careful analysis, as to just where the stopping point is. Moreover, inasmuch as a large part of the investment in any water proposition is in the base works, including the dam, forebays and tailrace, it becomes a relatively simple matter to prepare for and add successive units as they are economically needed and the business is developed.

The writer had a very interesting experience recently in going through a rather protracted discussion leading up to the introduction of Safe Harbor power into the City of Washington. A few years ago this would have been thought to be impossible because the only consideration then would have been the relatively low average cost of steam power and the relatively high cost of hydraulic power based on average river flow with limited capacities installed. When the engineers, however, presented their figures showing how the one power could be fitted into the other, the possible results were remarkable. It may be said also that some of these developments that have been made and those that will be made in the future are also made possible by a proper point of view in regard to the market. Not only does the modern engineer and power economist fit his sources of power very carefully together so as to get the greatest possible economic production, but an equally careful examination is made of the possible use of this power, the diversity of the various markets in reach, etc. Contracts can therefore be made at varying rates so that every customer is benefited and the company is better off.

**R. E. B. Sharp:** Under section II of the Appendix, Mr. Allner discusses the performance obtained by the dual operation of pumps and turbines. He states "a centrifugal pump that has its best efficiency under certain conditions of head, speed and discharge, for which it is designed, can be made to function as a turbine at the same head and would show the same efficiency though at reduced speed and discharge." This is equivalent to saying that for a given uniform efficiency for both conditions of operation the turbine losses and the pump losses will bear a given relation to each other. These losses, of course, will not be equal, with equal efficiency. It is true that in some cases the turbine and pump efficiencies are the same, as in Fig. 6, but this is not necessarily true for any centrifugal pump.

If the pump losses could be kept as low as the turbine losses, the pump efficiency would be higher than the turbine efficiency. The fact that pump efficiencies are generally lower than turbine efficiencies is evidence of the greater difficulty in keeping pump losses anywhere near as low as turbine losses.

Consider a design of pump where the runner contains vanes, which are long, and which have a small angle with the tangential at discharge (when operating as a pump). The diffusion losses through the runner would probably be relatively low with such a design, resulting in what is considered high pump efficiency, provided other parts are properly designed. When this runner is operated as a turbine, on the other hand, the efficiency might be good, as the long vane passages would result in effective guidance of the water, with friction losses negligible (where the specific speed is low). This design of pump, as a consequence, would show relatively high efficiency, as a pump, and also high efficiency as a turbine.

Consider another design of centrifugal pump provided with shorter length of vanes with a greater angle between these vanes at discharge (when operating as a pump) and the tangential. When operating as a pump the losses due to diffusion, caused by too great an angle between the vanes, and consequently too great a rate of area expansion, would result in relatively low efficiency as a pump. On the other hand, the steep vane angle and short passages would tend to give relatively high efficiency as a turbine.

In view of the above, the writer submits that there is no basis for the efficiency of any centrifugal pump necessarily being the same when operating as a pump as when operating as a turbine.

The I. P. Morris organization has developed a reversible pump-turbine for dual speed operation from a model having a runner 18 in. in diameter at the vane tips. The efficiency as a turbine, as obtained from test, was found to be 89.3 per cent and as a pump, 85.5 per cent. This model was designed to have both the turbine losses and the pump losses as small as practicable. It was realized that it would be more difficult to keep the pump losses small, than the turbine losses, and the runner was designed, to a large extent, to suit pump operation with the vanes fairly long and with an effort to keep the diffusion losses for pump operation low. Nevertheless, in accordance with the test, the pump losses proved to be 59 per cent greater than the turbine losses, as may be deduced from the efficiencies obtained.

A second model runner was tested, having the vanes at the tips more nearly radial. The test showed that efficiency, as a turbine, equaled 87.5 per cent and as a pump 80 per cent. In this case the pump losses proved to be 100 per cent greater than the turbine losses.

The dual speed motor generators required with reversible pump-turbines do not present difficult problems, according to one of the electrical manufacturers. For pump storage projects involving upward of 150-ft head, permitting the use of low specific speed Francis runners, there is no engineering obstacle preventing the use of reversible dual speed hydroelectric units with high efficiency under both conditions of operation. To obtain with such units the best pump efficiency, the amount of power input, when pumping, is materially greater than the power output when generating.

The operation of a pump-turbine at a single speed for reasonable economy, requires that both turbine and pump efficiency be as high as practicable. In addition to raising the efficiency-speed curves throughout the range, the higher the efficiency the closer together are the speeds at which maximum turbine efficiency and maximum pump efficiency occur. That is, as Mr. Lewis F. Moody has pointed out, on the basis of uniform head,

$$\frac{RPM_{T}}{RPM_{P}} = \sqrt{\text{Effic.}_{T} \times \text{Effic.}_{P}}.$$

The pumping operation, however, will necessarily be, to a great extent, against a higher head than when generating, with the consequent additional separation of the two speeds and reduction of efficiency at the common speed. Where, as generally would be the case, the turbine efficiency is decidedly higher than the pumping efficiency, the intersection of these curves, that is the common speed, would occur close to the maximum pumping efficiency. Therefore, the use of a single speed would result in securing almost the maximum pumping efficiency available, with the greater sacrifice in turbine efficiency.

**James E. Stewart:** The writer considers that Mr. Allner's paper very clearly brings out the modern conception that the main value of the utility hydro plant is capacity where there is not a high minimum stream flow.

Unless the flow at hydro stations is backed by natural storage or relatively low cost artificial storage, energy costs for hydro plants cannot usually compete with energy from the modern steam station. In general this statement leaves the steam stations as the cheapest energy makers for most of the population of the United States. The exceptions are where cheap storage is available in lakes, glaciers, snow fields, lava beds, etc. These areas in general are limited to mountainous or glacial regions. In Canada over 95 per cent of the utility load is carried by water power because the high low water flow makes hydro power cheaper per kilowatt hour than steam. In this connection it is to be remembered that practically all Canadian water power developments are in glaciated areas and in addition many are in mountainous territory. There are regions in the United States, particularly in the Rocky and Cascade Mountains and to a lesser extent in the high rain-fall regions of the Appalachian Mountains where water power can compete with steam on an energy basis alone. Elsewhere with rare exceptions it is only on a capacity basis, or energy and capacity basis that water power works out more economically than steam, and then in general the best economy has proved to be a combination of steam and water power.

**Ireal A. Winter:** The part of the paper dealing with hydro-regeneration equipment is of especial interest. This is a pioneer work in the States and shows in a concrete way what can be expected by further research along this line. It is the writer's opinion that the use of hydro-power has a most important part to play in the economics of interconnected power systems in the future. The subject matter discussed in the paper points the way to a new line of thinking for the hydroelectric interests of the country. The time is fast approaching when the conception of a wide use hydro-regeneration will mature into a concrete fact. Further specific evidence of what the field offers, such as brought out in the paper, will do much to accelerate the development and installation of suitable equipment to the economic advantage of the electrical industry.

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# Safe Harbor Project

BY N. B. HIGGINS*

Member, A.I.E.E.

***Synopsis.***—*The Safe Harbor Water Power Corporation has recently completed the dam and initial section of the power house to develop the fall of the Susquehanna river between the Holtwood project backwater and Columbia, Pennsylvania. This development, when completed, will be one of the largest hydroelectric developments in the United States.*

*In the initial project there will be installed 255,000 turbine horsepower, and in the completed project 510,000 turbine horsepower. One of the most notable features is the 42,500-hp. Kaplan turbines, the most powerful ever built and the largest in physical dimensions so far installed on this continent.*

*In the average year, with full utilization, the initial project will generate over 800,000,000 kw-hr. for distribution through the transmission system of the Pennsylvania Water and Power Company to Baltimore, Maryland, and Pennsylvania customers. Transmission to Baltimore will be at 230 kv. and to Pennsylvania customers at 69 kv. and 132 kv.*

*The power house and dam have a combined length of 5,000 ft.; the length of the dam is 4,084 ft., and the ultimate length of the power house is 916 ft. The spillway length is 1,810 ft.; the spillway is equipped for its entire length with crest gates, of which there are thirty-two 48 ft. long and 35 ft. high. The discharge capacity of the spillway at normal elevation 225.0, is 970,000 c.f.s., and at forebay elevation 227.0 (ultimate) 1,150,000 c.f.s.*

*The lake created by the dam impounds a useful storage of 3 billion cu. ft., and has the following dimensions: length 10 mi., width 0.4 mi. to 2.0 mi.; area 10.5 sq. mi.*

*On the east side of the river, 8.5 mi. of the Columbia & Port Deposit Branch of The Pennsylvania Railroad were raised a maximum of 8 ft.*

*The delivery of power to Baltimore was started 1 year, 8 months, and 7 days after work was started on the project site, an outstanding achievement in the annals of hydroelectric projects of this magnitude.*

* * * * *

## INTRODUCTION

THE lower Susquehanna basin between Columbia, Pa. and the Chesapeake bay, attracted the attention of waterpower promoters early in the history of hydroelectric development. Between these points there is a difference in elevation of about 227.0 ft. Several schemes were projected by rival promoters and engineers. Finally a merger of certain interests led to the formation of the McCall Ferry Power Company, which began work near McCall Ferry, Pa. This company failed in 1907 and was succeeded by the Pennsylvania Water and Power Company.

The initial development, now known as the Holtwood project, went into operation in 1910. This left undeveloped and available a fall of about 100 ft. below, and 57 ft. above Holtwood. Of these possible developments, the lower (Conowingo project) was constructed and went into operation in 1928.

The Safe Harbor Water Power Corporation was formed by the Aldred interests, who also own and operate the Pennsylvania Water and Power Company's Holtwood project, eight miles downstream from Safe Harbor. These properties, together with the steam stations of the Consolidated Gas Electric Light and Power Company in Baltimore, are interconnected and form a unified system operated for the best overall economy throughout.

## OUTLINE OF PROJECT

The development of the fall between the Holtwood pool and Columbia by the Safe Harbor Water Power Corp., is the subject of this paper. The site of the project is about 1,100 ft. upstream from the mouth of Conestoga creek. This development, when completed, will have an installed capacity of 510,000 hp., in twelve Kaplan turbines, each of 42,500 hp. capacity, operating at a speed of 109.1 r.p.m. under a head of 55 ft. Ten of these turbines will drive 36,000-kva., 60-cycle, three-phase, 80 per cent—100 per cent power factor, 13,800-volt generators, and two will drive 37,500-kva., 25-cycle, single-phase, 80 per cent power factor, 13,300-volt generators. There are also included in the ultimate plan, four 25 cycle/60 cycle frequency changers of the outdoor type; the generating end will be rated at 31,250 kva., 80 per cent power factor, 300 r.p.m., 13,300 volts.

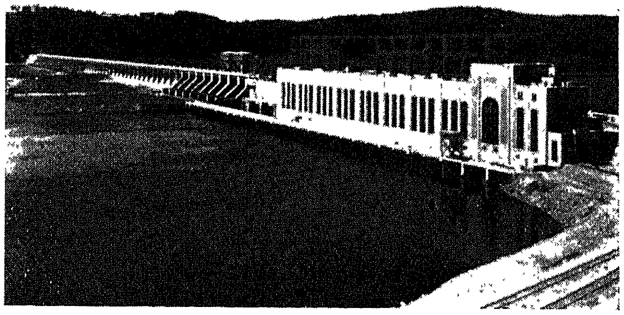

FIG. 1—GENERAL VIEW OF THE SAFE HARBOR PROJECT

The initial step of the development includes five 60-cycle units and one 25-cycle unit, and one frequency changer; four 60-cycle units are now in operation, and it is expected that another 60-cycle unit, one 25-cycle unit, and a frequency changer will be installed before the end of 1933.

A major problem in electrical design at Safe Harbor has been to produce a flexible layout, which will permit the installation as required of equipment for generating,

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*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

transforming, and transmitting 60 cycle, three-phase, and 25 cycle, single-phase. All generating equipment and the 60-cycle low-tension bus are located in the power house. All 60-cycle transformers are of the outdoor type, and located adjacent to the power house.

The combined 69-kv. and 230-kv., 60-cycle substation will ultimately be located on the top of the hill, directly east of the power house. The frequency changers, the 25-cycle low-tension bus, and the 132-kv., 25-cycle step-up substation will be located east of the power house.

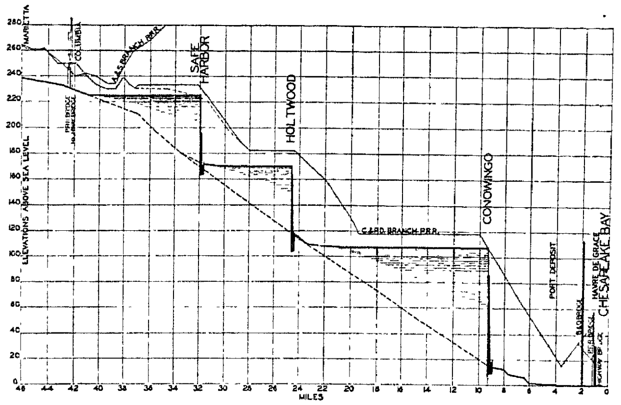

Fig. 2—Profile of the Susquehanna River from Columbia, Pa. to Chesapeake Bay

One 230-kv. circuit has been constructed between Safe Harbor and the Westport station of the Consolidated Gas Electric Light and Power Company in Baltimore, Maryland. Another 230-kv. circuit will be constructed to Baltimore within the next few years, over a separate right-of-way entering the city from the east.

A 69-kv. double-circuit transmission line, about one mile in length, has been constructed to tie Safe Harbor into the existing 69-kv. system of the Pennsylvania Water and Power Company. This connection is made to the Holtwood circuits at a new switching station at Lehman Farm.

The power house is in line with, and forms a continuation of the dam. The substructure is of reinforced concrete, and the superstructure of brick and tile.

The total combined length of the concrete dam and power house is 5,000 ft., made up as follows: power house, 916 ft.; bulkhead and abutments, 2,274 ft.; spillway, of the ogee type, 1,810 ft. The entire spillway is equipped with crest gates. Although the highest flood of record is estimated to have been 725,000 c.f.s., the spillway was dimensioned for a maximum discharge of 970,000 c.f.s. at forebay elevation 225.0, and 1,150,000 c.f.s. at forebay elevation 227.0.

The forebay is enclosed by a skimmer wall and dyke to prevent the entry of trash and ice.

Fig. 3 shows the general arrangement plan of structures.

A general description of the project, with particular attention to the principal features, follows:

## The Susquehanna River

In extent of drainage basin, and in total and average runoff, the Susquehanna river is the largest river flowing into the North Atlantic ocean, with the exception of the St. Lawrence. Its watershed includes 27,400 sq. mi. in the states of New York, Pennsylvania, and Maryland. Yet, in spite of this vast tributary area, the stream itself is of little use in commerce. One of the principal reasons for this is the unique fact that the steep slopes in the course of the river occur in the lower reaches, where the stream has cut its way through the Piedmont plateau. Tidewater from Chesapeake bay extends only five or six miles up the river and there is practically no navigation above the tidewater limit.

From Columbia to Tidewater, a distance of 39 mi., the river is walled in by steep bluffs or hills, and the main channel varies in width from a few hundred yards to almost two miles. As a result of these conditions there has been no industrial development, other than transportation, in this reach of the river; the tracks of the Columbia and Port Deposit Railroad skirt the eastern shore of the river for the entire distance.

These conditions of rapid descent, steep banks, and the absence of populous towns in a region in close proximity to large industrial centers, made this reach of the river attractive from a power development standpoint.

## Project Site

Many of the flowage rights required were already in the hands of the Pennsylvania Water and Power Company as early as 1910. In the twenty years intervening much additional land had been acquired, so that most of the real estate and flowage rights required for the project had been obtained a number of years before initiating the work.

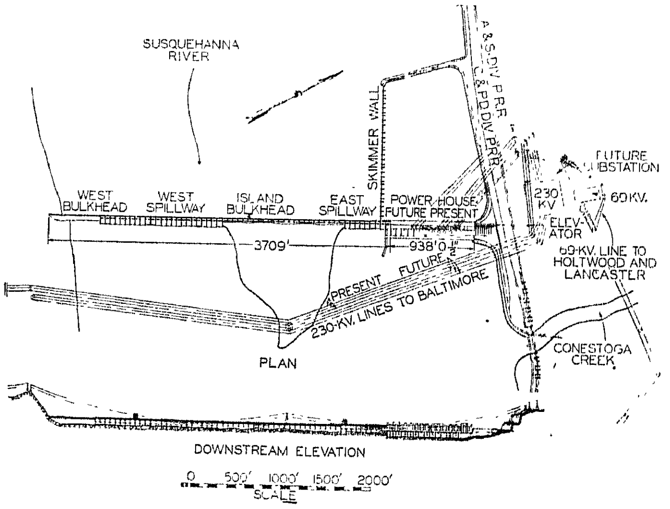

Fig. 3—General Layout of Structures

During this period the engineering staff of the Pennsylvania Water and Power Company made numerous studies of the power possibilities of this project.

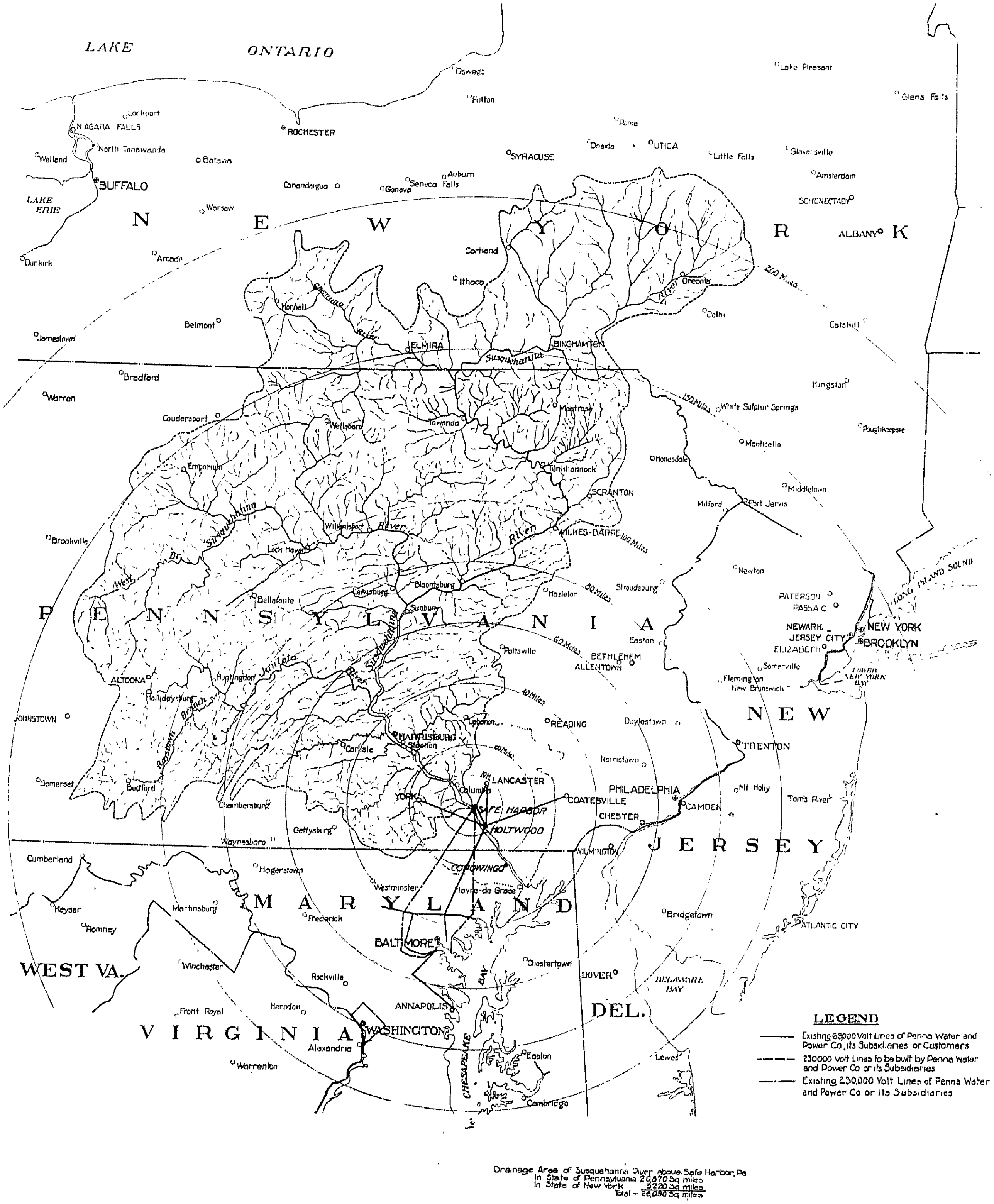

FIG. 4—MAP OF THE SUSQUEHANNA RIVER DRAINAGE AREA

Several sites were considered within a range of two miles upstream of the mouth of Conestoga creek before the site was finally selected. During 1928 an extensive program of core borings was conducted and foundation conditions were found to be satisfactory for dam construction.

A location for the construction plant and classification yards was an important consideration. Owing to the steep banks and bordering railroads, there was no favorable site along the river. The valley of Conestoga creek, just above the mouth, was found very favorable and used for this purpose. A large island in the middle of the river that could be utilized to advantage for river diversion, as well as being a suitable site for the concrete mixing plant and materials distributing yard, was an important feature in selecting the project site.

### RESERVOIR CONDITIONS

Backwater from the dam extends 10 mi. upstream and forms a lake varying in width from 0.4 mi. to almost 2 mi., covering an area of 10.5 sq. mi. The water stored in the top foot of the pond is approximately 310 million cu. ft.; the total useful storage is about 3 billion cu. ft.

On the east side of the river, 8.5 mi. of the C. & P. D. Branch of The Pennsylvania Railroad had to be raised, and on the west side some highway relocation was required; otherwise, improvements effected within the reservoir limits were negligible. The maximum rise in track is 8.5 ft., at the dam site; the elevation of top of rail above normal pond level is 8 ft. The railroad company took advantage of the favorable conditions prevailing during the track changes incident to the construction of the project, to widen the roadbed of the C. & P. D. Railroad to accommodate two tracks, which cost was borne by the railroad company. Approximately 270,000 cu. yd. of rock excavation and 1,250,000 cu. yd. of rock fill were required completely to relocate and double-track this section of the railroad.

### HYDRAULIC STRUCTURES

It was desired to obtain full control of the forebay level for all possible river flows and to maintain constantly the maximum permissible forebay elevation, except when lowering would be desirable to make use of storage. This required a spillway that could be controlled with crest gates for its full length, and capable of discharging the greatest flood assumed possible at the given forebay elevation of 225.0.

A number of comparative estimates was made to determine the most economical combination of size and number of gates to produce these discharges. The final analysis resulted in selecting 32 gates for openings 35 ft. in height and 48 ft. in width; tops of gates are 5 ft. above initial normal pond level, to prevent excessive loss of water from wind action. Other factors in establishing the clear opening were physical dimensions, limitations in transportation, field handling, and size of debris. Twenty-four gates are located in the channel west of Else island and 8 in the channel east of Else island.

At normal forebay level each flood gate will discharge about 30,000 c.f.s.; the west spillway has a discharge capacity of 720,000 c.f.s., which is equal to the maximum flood of record.

The bulkhead sections are conventional gravity structures, designed for compression over the entire foundation joint for headwater at elevation 228.0, 10,000 lb. per lineal foot of ice pressure at the same elevation and uplift corresponding to full head at the heel, decreasing to tailwater head at the toe following a gradient determined by the foundation drainage system.

The design of the spillway is based on the same assumptions, except that ice pressure here was reduced to 4,000 lb. per lineal foot, acting on the gates, and transmitted to piers. The lower assumption was considered justified as a compressed air bubbler system has been incorporated in the design to prevent ice pressure from acting on the gates.

The spillway has an overhung crest and a large bucket type of apron; otherwise, it is of the usual ogee cross-section. The shapes of the apron, spillway nappe, and pier noses, were determined by model tests in the Alden laboratory of the Worcester Polytechnic Institute. The dam stands on a sound rock foundation of quartz, mica schist, and phyllite. Because of the excellent quality of the foundation, the strike of the folds, and the dips of the stratum, no cutoff trench was required; natural conditions made it possible, in effect, to obtain cutoff trench advantages at little additional cost. Rock was removed by blasting operations; the average depth of excavation was 11 ft.

With the velocities and unit discharges produced by a 30-ft. overflow, it was recognized that erosion should be expected in the hardest of rock. The primary purpose of the apron tests was to locate the point of attack as far downstream, from the toe of the dam, as possible. Experience with the prototype has thus far confirmed the shape of the discharge trajectory.

The crest gate equipment consists of 28 single-leaf Stoney flood gates, and 4 double-leaf regulating gates—the lower leaf of which is a Stoney gate and the upper leaf a fixed roller gate; there are also two emergency gates with fixed rollers. The upper leaves of the four regulating gates are operated normally by lowering them and discharging the water over the top. By means of these gates, close regulation of pond level can be maintained, as well as providing for the easy removal of floating debris and ice with the minimum waste of water. Debris and ice usually will accumulate along the skimmer wall, for which reason the four regulating gates are located adjacent to the power house. The upper leaves of the regulating gates are operated with individual hoists located in a tunnel directly under each gate, in the body of the dam. The hoist motors for the regulating gates have operating controls at the hoists and in the power house switch room.

Two gantry cranes of 150-ton capacity each, are provided to handle all crest gate equipment. These cranes are served from a trolley bus on the operating bridge; one of the cranes is equipped, also, with a gasoline engine-generator set for emergency operation. Attachment of gates to the gantries is by means of a lifting beam.

The flood gates are of the usual design of horizontal fabricated girders supporting a skin plate through vertical intermediate beams. The respective weights are 86 tons each for the flood gates (excluding roller trains), and 100 tons each (including fixed wheels) for the emergency gates.

The vertical seals between gates and guides are made of a U-shaped bronze spring plate, with a wearing shoe sliding on an Ascoloy bearing plate welded to the guides; the bottom seal is of molded rubber bolted to the gate, and seats on the steel gate sill in the spillway crest. Between upper and lower leaves of the regulating gates, horizontal brass spring seals are used.

Roller trains with cast steel rollers are provided for flood gates and lower leaf regulating gates, and are connected to gates and piers with equalizer sheaves. Emergency gates and upper leaf regulating gates have bronze-bushed, fixed rolled-steel wheels.

Due to their size, the gates could not be shipped fully assembled, but no gate was split up into more than five pieces. Gates were assembled on two concrete erection platforms built into the island bulkhead, which also serve as storage platforms for the emergency gates.

The guides were not grouted into grooves left in the pier concrete, the usual practise, but were tied together with bracing, so as to form a rigid frame of all the guides in one pier, erected in place before the pier concrete was poured, and held to line during concreting operations with temporary struts. The quality of alinement obtained is excellent.

The gantry operating bridge consists of two T-shaped reinforced concrete beams. There is no deck between the beams, so that gates suspended from gantries can travel with their bottom edge below the level of the gantry rails, whereby shorter gantries are used, and a considerable quantity of concrete was saved.

The main reinforcement of the bridge girders consists of a structural steel truss, dimensioned to take dead loads resulting from forms and concrete. For all live loads, the truss steel, supplemented with bars, forms the concrete girder reinforcement. With this construction, no shoring was required under the forms, as all formwork could be suspended from the trusses. A truss, rather than a plate girder, was chosen for economy in dead weight, and to obtain a more homogeneous structure in which the concrete carries the stress, instead of being merely added weight.

To permit the gantries to travel over both the east and west spillways, the operating bridge extends over the island bulkhead, where the upstream gantry rail is supported directly on the mass concrete. On the power house side, the operating bridge extends about 50 ft. beyond the first gate, and the railroad, as well as the craneway of the power house intake deck, overlaps into this space. This makes it possible to run railroad cars under the spillway gantries, as well as to transfer loads from the intake gantries to the spillway gantries.

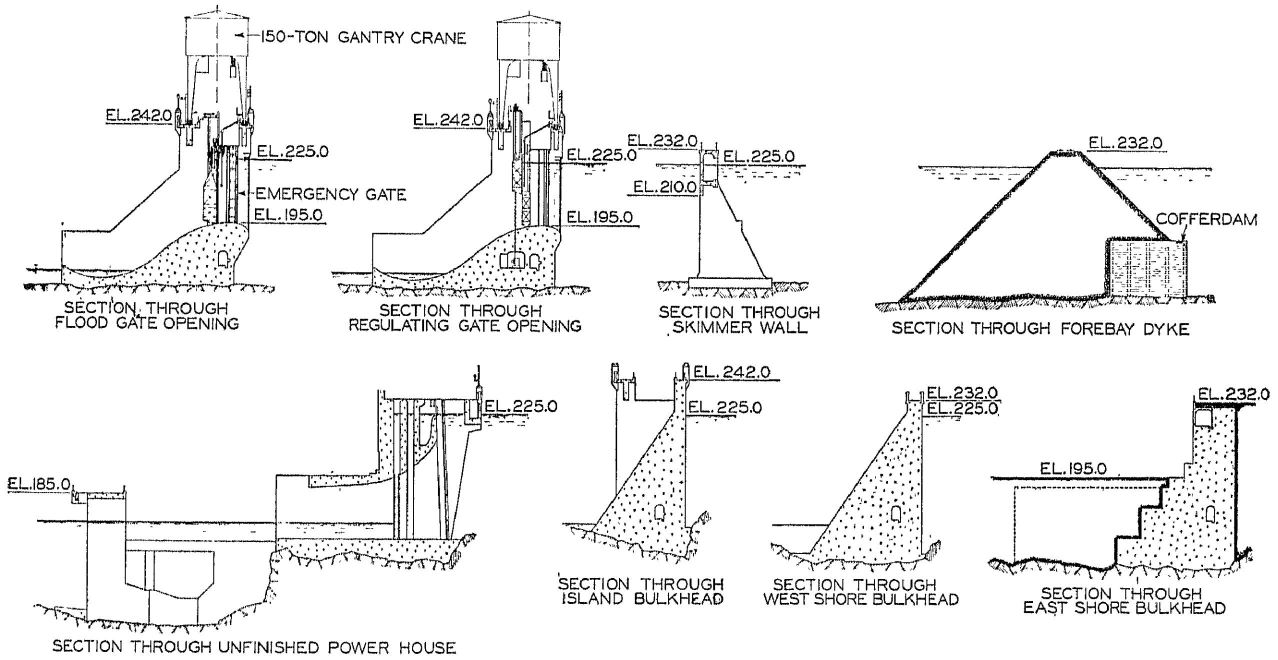
150-TON GANTRY CRANE
EL.242.0
EL.225.0
EMERGENCY GATE
EL.195.0
SECTION THROUGH FLOOD GATE OPENING
EL.242.0
EL.225.0
EL.195.0
SECTION THROUGH REGULATING GATE OPENING
EL.232.0
EL.225.0
EL.210.0
SECTION THROUGH SKIMMER WALL
EL.232.0
COFFERDAM
SECTION THROUGH FOREBAY DYKE
EL.185.0
EL.225.0
SECTION THROUGH UNFINISHED POWER HOUSE
EL.242.0
EL.225.0
SECTION THROUGH ISLAND BULKHEAD
EL.232.0
EL.225.0
SECTION THROUGH WEST SHORE BULKHEAD
EL.232.0
EL.195.0
SECTION THROUGH EAST SHORE BULKHEAD

Fig. 5—Typical Cross-Section Through Hydraulic Structures

It is believed that every reasonable precaution has been taken to insure the safe operation of the crest gate equipment under the most unfavorable combination of circumstances. The following features are noted:

a. Large excess capacity of the gantry cranes.

b. One crane can handle gates with sufficient rapidity to meet any normal condition; two cranes are provided.

c. Different sources of power for the gantries.

d. One crane is provided with a gas engine generating set.

e. Equipment to electrically heat the roller tracks and seal plates on the gate guides.

f. A compressed air bubbling system to prevent ice formation on the upstream side of the gates.

## FOREBAY

Experience at Holtwood had demonstrated the value of a fully enclosed forebay when turbine intakes are shallow, and this feature was incorporated into the Safe Harbor design. The forebay is enclosed by a skimmer wall 1,500 ft. long, extending upstream at right angles to the dam, to a junction with a rock-filled dyke about 1,000 ft. in length, extending from the river bank. The skimmer wall intersects the dam at the pier between the first and second regulating gates. A regulating gate discharging from the forebay provides for the disposal of trash that may enter, or ice that may form in the forebay.

The lower edge of the skimmer wall is, at elevation 210.0, 15 ft. below normal water level. Under the full discharge of twelve turbines, the water velocity through the skimmer wall should not exceed 1.75 ft. per second. This velocity is believed to be sufficiently low to prevent floating trash from entering the forebay.

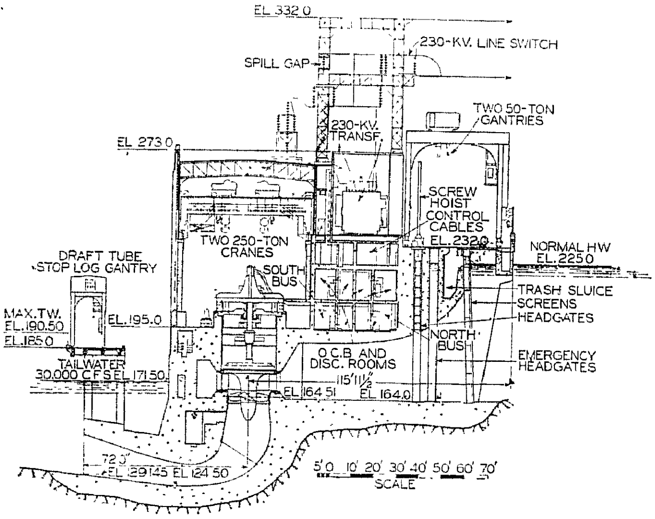

Fig. 6—Typical Power House Cross-Section

The skimmer wall structure is a vertical curtain of concrete, supported on piers 53 ft. on centers. It was designed to withstand an ice pressure of 4,000 lb. per lineal foot from the river side, or 2,000 lb. per lineal foot from the forebay side. With a view to eliminating ice pressure entirely, a compressed air bubbler system is provided, with outlets on both sides of the wall. The top was developed into a walkway 8 ft. wide. The curtain wall, supporting piers, and struts are of structural steel encased in concrete. This type of construction effected a large saving in construction time.

## POWER HOUSE

The site selected for the power house is in the low-water channel of the river near the Lancaster county shore; minimum excavation for power house and tailrace was an important consideration in the selection of this site. Fig. 6, a transverse section, and Fig. 7, sectional plans and elevations through the power house, show the principal features.

The ultimate length of the power house will be 916 ft.; the initial section is 642 ft. long, with space for seven units. A space 506 ft. long is occupied by the four completed and three uncompleted main units, and two service units; 36 ft. by the equipment assembly space, and the 100 ft. at the shore end by filter plant, boiler room, storerooms, repair shop, administrative and engineering offices, and other general utility rooms; the width is 56.04 ft. and the height above operating floor is 78 ft. A railroad connection extends into the generator room assembly bay.

The physical dimensions of the Safe Harbor turbines are the largest for this type of unit so far installed in this country. The maximum scroll case and draft tube width is 55 ft.; the thickness of piers between units is 7 ft., making the unit spacing 62 ft. Below the water line all contraction joints are sealed with crimped sealing strips made of 24 oz. copper, while construction joints between lifts of concrete are sealed with flat copper strips.

Offsetting by 2 ft. 6 in. the transverse center line of units with the transverse centerline of the intakes presented a difficulty in lining up the piers between waterways which was overcome by slightly tilting the upper part of the draft tube.

The characteristics of the turbines selected required a deep draft tube, but the influence of this on volume of tailrace excavation was reduced by sloping the bottom of the outflow end of the tube upward at the steepest permissible angle without affecting the draft tube efficiency.

From low point to exit the draft tube is divided into two equal outlets by a 5-ft. pier. For unwatering, the draft tube can be sealed by a set of sliding gates. A 25-ton gantry crane is provided to handle the gates from a bridge over the draft tubes.

From the draft tube outlets the tailrace floor slopes upward to intersect the natural river bed at an angle of 6 deg. The maximum depth of rock excavation was about 40 ft.; 180,000 cu. yds. of solid rock was excavated to form the tailrace channel. This excavation is the total for the ultimate plant; likewise, the substructure was excavated for all future units. The principal reasons for this procedure at this time are: low cost, elimination of subaqueous excavation in the future, simplification of future power house extension, and a deficiency of rock fill material from required excavation.

The intake portion of the power house substructure for the five future units was completed, excepting that no intake gate hoists or screens were installed. The intake gates for future units were an important part of the scheme for the control and discharge of the river flow during closure of the last cofferdam.

The floors of the intakes are level at approximately the same elevation as the floor of the forebay; each intake consists of three water passages, with smooth sloping bell mouth at the intake. The cross-section of the water passages at the head gates measures 15 ft. 8 in. wide by 29 ft. 4½ in. high. Each water passage is controlled by one intake gate; slots are provided in the head works in front of head gates for the placing of emergency gates when head gates are taken out of service. Velocities through the gross area of the intake cross-sections vary from 3.32 ft. per sec. at entry to 7.25 ft. per sec. at the scroll case intake.

The center gate of each intake travels on fixed rollers, and is operated with a motor-driven screw hoist; the two outside gates are sliding gates, and are handled with a 50-ton intake gantry crane, of which two are provided. The screw-hoist-operated gate can be raised or lowered under full unbalanced water pressure. The sliding gates are designed to be handled under balanced water pressure only. Emergency valves are provided in the sliding gates for filling the intakes in event of screw hoist motor failure.

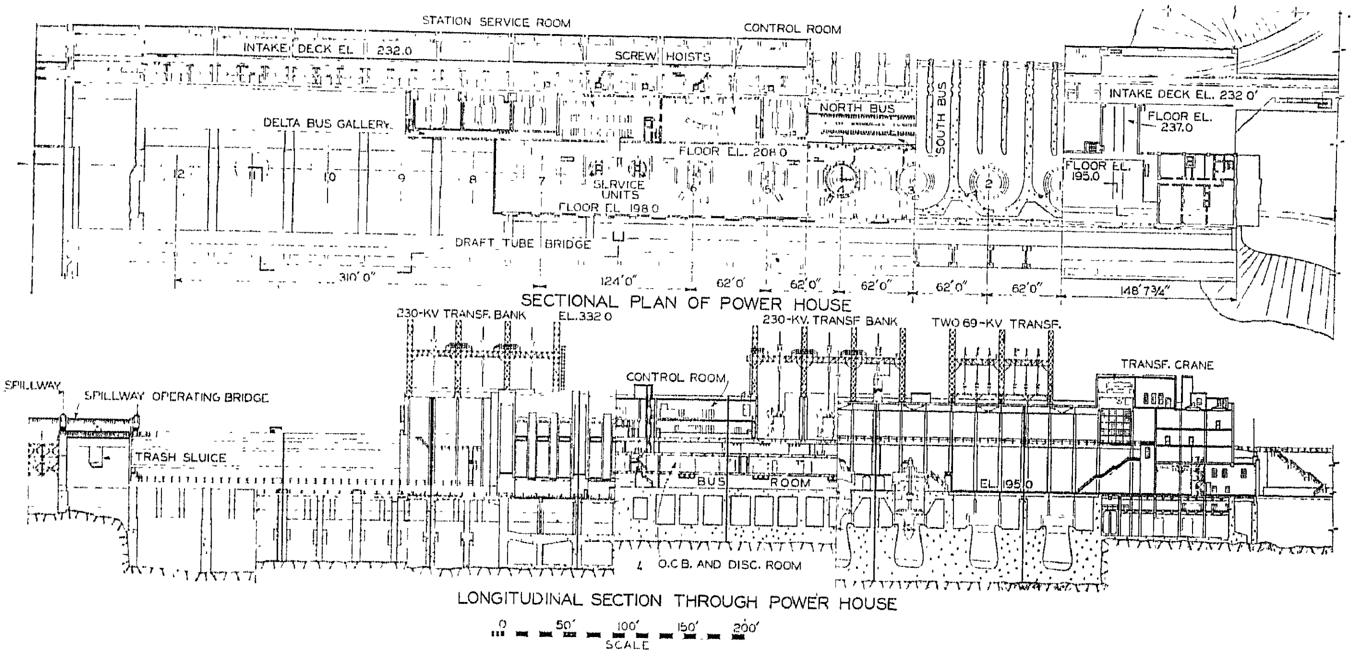

FIG. 7—POWER HOUSE SECTIONAL PLANS AND ELEVATIONS

The omission of hoisting mechanism on two-thirds of all head-gates resulted in a substantial saving in cost, and slows up the starting operation to a negligible degree, as a unit can be started with the center gate alone open.

The emergency gates are similar to, and are handled in the same manner as the sliding headgates.

The seals of the intake gate equipment are of molded rubber and bronze spring plates.

Gate guides were fully erected for the intakes of two units before concrete was poured; the erection procedure was the same as that used on the spillway gates.

A single intake screen is made up into five vertical sections 12 ft. high and 18 ft. wide, and slides in slots similar to the gate slots. The face of the screen has a batter of 1 in 24. Individual screen bars and their supporting frame are designed for an unbalanced head of 15 ft. of water. The vertical screen bars were designed to offer a minimum resistance in the water passages; this developed to be a shape similar to that of an airplane strut. Intermediate horizontal and vertical supports for the screen bars are flat plates with an elliptically shaped leading edge. In addition to reducing the loss of head, a flow free of eddies will decrease the tendency for frazil ice to adhere to the screens. Intake screens are of welded construction throughout.

There is provision for a mechanical trash rake, but the rake will be installed in the layout only if found necessary. Surface trash and ice that may collect at the turbine intakes can be discharged directly over the screens into the trash sluice built into the substructure. The crest elevation of the sluice is one foot below normal forebay level, and is closed off from the forebay by gates, which, when raised, permit the discharge of all floating debris into the sluice, from where it is carried directly to the tailrace. Compressed air can be discharged at points on the periphery of the intakes to dislodge and float waterlogged debris.

Electric heating of screens to prevent adherence of frazil ice has been provided for to the extent that conduit has been installed to distribute power for this purpose on the intake deck. A tunnel is provided on the upstream side of the intake deck to house transformers and a screen heating bus. This tunnel serves at the same time as a second skimmer wall to keep the intakes clear of debris.

Another means to reduce or eliminate ice troubles in the intakes is a provision to discharge the air from the exhaust duct tunnel of the power house ventilating systems, into the space over the screens and below the intake deck. The intake deck is covered with floor plates to provide necessary working space, and to eliminate the need of railings. The intake deck is served by a standard gage track, and an 8-ft. gage track for transformer handling.

There is but one main operating floor in the generator room. Consolidating the hydraulic operating equipment simplified the work of attendants, as well as reduced the height of the power house. The choice of umbrella type generators also effected a saving in power house height; however, the concentrated reactions from generator and turbine loads on the concrete of the scroll case, which is, also, highly stressed from water pressure, produced a complicated structural problem. This required the use of high quality, heavily reinforced concrete, in order to insure density and high strength. The same consideration applied to the slab over the intake between headgates and scroll case, which also forms the floor of the 13.8-kv. bus room, as it is highly essential that the bus room be absolutely dry and that no cracks develop in its floor, or upstream wall, which is also exposed to water pressure. As an additional precaution against water seepage, the bus room has a false floor and false upstream wall, with an air space between the latter and the concrete bulkhead, and a gravel fill between floor topping and intake roof slab. Any water that may seep through the upstream wall or floor will be intercepted and discharged to the power house drainage system.

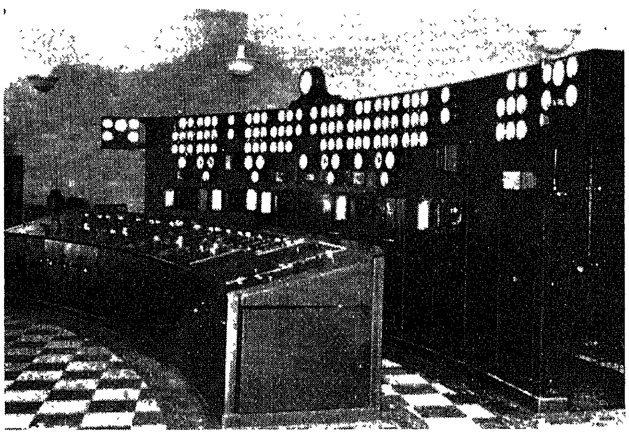

FIG. 8—VIEW IN CONTROL ROOM

The power house superstructure is of steel frame, with buff exterior brick and glazed stippled tile interior curtain walls, and concrete roof. The electrical bay is described under "Electrical Structures."

The water- and oil-proofing of the transformer deck consists of a membrane of 24 oz. copper, which is protected with a three-in. concrete slab. The copper lining extends two feet all around above the floor of the pocket.

For the handling of transformers between the generator room floor where they are unloaded from railroad cars, to the transformer deck, an enclosed transfer bay is provided at the shore end of the building. This structure is elevated above and extends across the generator room. This bay is equipped with a special 250-ton crane operating at right angles to the generator room axis, to hoist and transport transformers between the generator room floor and the intake deck, where they can be placed on a transformer car and transported to their operating positions.

In the solution of this arrangement, it was found necessary to lower the runway of the generator room cranes to the same elevation as the transformer deck. This condition required a special design of short-legged gantry crane for the generator room. Two 250-ton cranes of this type have been installed; each crane carries two 125-ton traveling hoists and two 15-ton auxiliary hoists. These two cranes proved to be important factors in the speed with which machinery was installed.

### ARRANGEMENT OF ELECTRICAL STRUCTURES

A cross-section of the power house is shown in Fig. 6. The electrical bay is between the generator room and the intake structures. It consists of three floors housing switching equipment. The lowest floor is occupied by the two buses and their taps; the second floor houses oil circuit breakers and disconnecting switches. The third floor contains the potential transformers and reactors. A vertical reinforced concrete fire wall separates the two buses and their associated switching equipment. Crosses are made only at those points where taps are taken off to machines, and special attention has been paid to making these vapor-tight.

Above the electrical bay are located the transformer pockets, each approximately 40 ft. by 30 ft. in size and separated by vertical fire walls one foot thick. Below each transformer there is a basin, drained to the tailrace and of sufficient size to accommodate all of the oil in the tank.

The takeoff structure supporting the isolating transformer disconnectors, the lightning arrester disconnectors, and the outgoing spans across the forebay is located directly above the transformers. Safe and quick maintenance on all switching equipment on this structure is made possible by a complete system of access ladders and working platforms.

In the center of the station a space 165 ft. in length above the electrical bay is devoted to the control and terminal rooms, batteries, station service transformers, and station service switchboards.

The control room (Fig. 8) is 83 ft. by 37 ft. and is located on the top floor of the control building. A terminal and conduit room is located below it. The switchboard is made up of three semi-circular boards consisting of a sloping bench, and vertical instrument and relay boards. Along the front and rear walls of the room are located the house service control board and the switchboard for the temporary line relays (which will later be transferred to the substation), the temperature indicators, river control, battery distribution, annunciators, totalizing and other miscellaneous controls.

### 60-Cycle Generating System

The four 60-cycle generators now in operation are installed in unit spaces Nos. 3, 4, 5 and 6. Fig. 9 is the main one-line diagram for the installation of these units.

In accordance with present plans, there will be ultimately ten 60-cycle main units occupying positions Nos. 3 to 12, inclusive. The 60-cycle generation is at 13,800 volts, three-phase, and ultimately will feed into a double bus system of eight sections, with four sections per bus. There will be supplied from this bus three 230-kv. step-up transformer banks and three 69-kv. step-up banks. Equipment is connected to the bus by selector oil circuit breakers. Reactors will be installed as needed to hold the short circuit values below 1,500,000 kva.

Only the simplest high voltage switching is provided at the power house. This consists of a motor-driven isolating disconnect with ground switches, for each transformer. The lightning arresters, spill gaps, and the lightning arrester disconnecting switches for protection of the transformers are also located at the power house, one set being connected to the outgoing leads of each transformer.

At the present time there is no high-tension bus, each transformer bank being connected directly to a transmission line. Either or both of the two 230-kv. banks can be tied to the single 230-kv. Baltimore circuit.

In the preliminary designs of the station, comparative studies were made of several layouts; however, the probable use of frequency changers for railway supply, the necessity for the use of two transmission voltages, considerations of existing system operating connections, and the reduction of early investment in costly high-voltage switching equipment, led to the adoption of the existing plan.

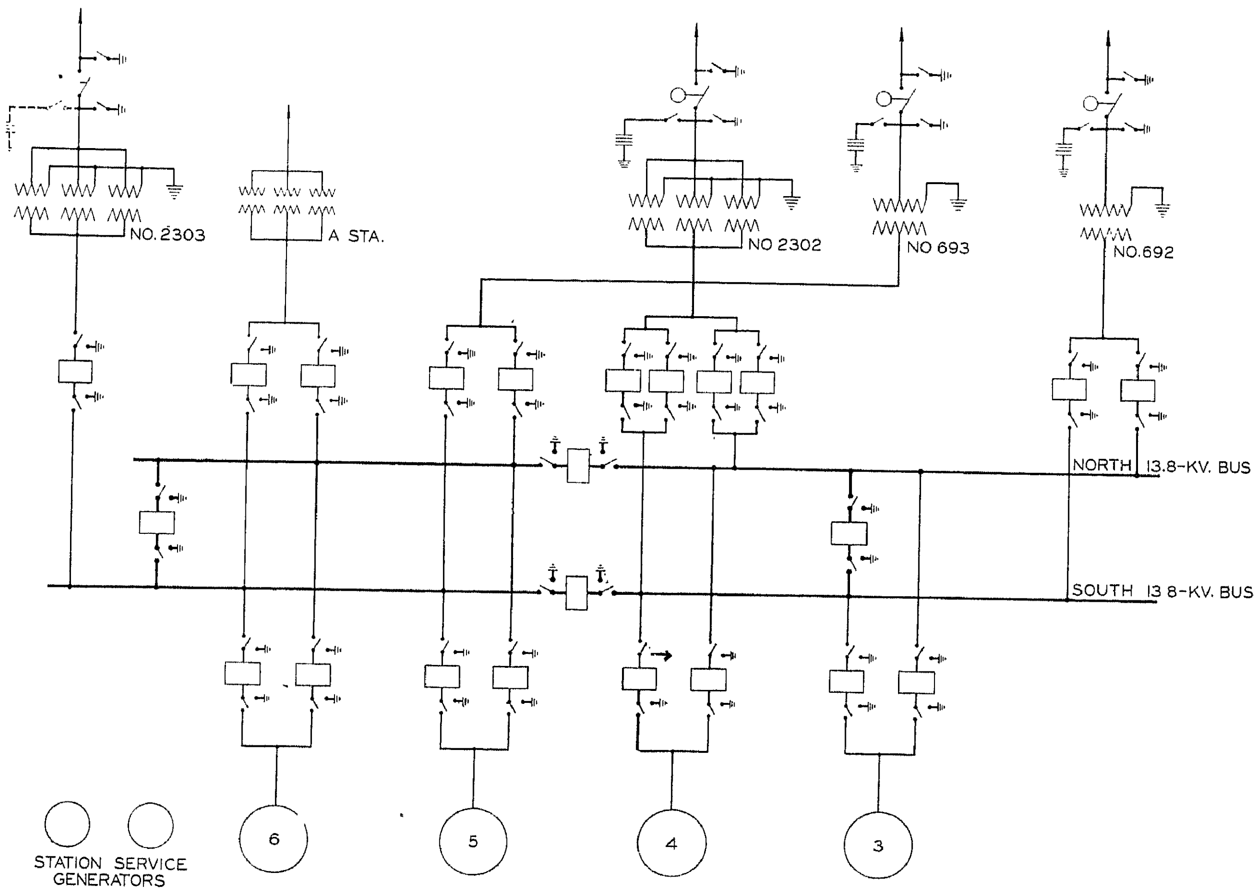

Fig. 9—Single-Line Diagram, 13.8-Kv. Main Bus

### 60-Cycle Generators

There are now installed four three-phase generators, each rated at 36,000 kva., 80 per cent—100 per cent power factor, 13,800 volts at 80 deg. cent. temperature rise on the armature and field. The generators are insulated throughout with Class B material. While it was not believed that machines of this size and importance should be operated continuously at the 80 deg. cent. temperature rise, it was decided that excitation should be provided to permit development of the rating corresponding to this rise for use during peaks or emergencies. Normal operation at approximately

28,000 kw., 90 per cent power factor falls within the 60 deg. cent. temperature rise on both armature and field, generally accepted as conservative design practise for this class of insulating material.

The generators are of the overhung rotor type with water-cooled guide and thrust bearings combined in a single housing below the rotor; the guide bearing and the thrust bearing are of the adjustable segmental shoe type; the thrust bearing is designed to carry a total weight of 1,500,000 lb., including a water thrust of 1,100,000 lb.

These machines are designed to withstand overspeed to 231 per cent of normal, which value, like that of the water thrust, is somewhat greater than usual on account of the characteristics of the Kaplan turbines.

The generators are 29 ft. 2 in. in diameter and are 29 ft. in height measured from the lower face of the coupling to the top of the Kaplan head. The weight of a complete machine is approximately 400 tons.

The manufacturers of the generators cooperated in the design of the machines in order to make parts interchangeable as far as possible. Those parts exposed in the generator room are identical in appearance.

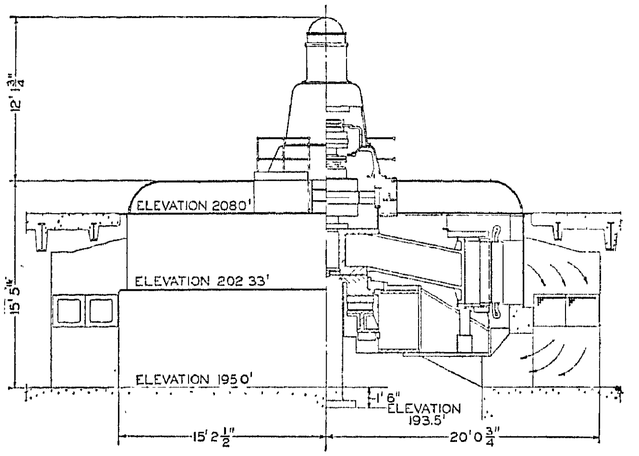

Fig. 10—Typical Cross-Section Through a Generator

A closed system of recirculating air is employed for cooling the main units. Air is introduced below the rotor and is forced by fans attached to the rotor through the windings into an eccentric frame, which serves as a duct to collect and conduct the hot air to the surface air coolers located on diametrically opposite sides of the machines, Fig. 10. The air path is totally enclosed throughout; the ducts are equipped with louvres which may be opened as required to bleed air for heating the generator room. A gravity system of water supplied from the forebay serves these coolers. The closed system of ventilation was selected rather than open ventilation for the following reasons: reduction in space; better control of generator temperatures; better fire fighting possibilities, and the exclusion of foreign material (particularly construction dirt).

The direct-connected pilot exciters are provided with slip rings from which power is taken to drive the governor fly ball motors. These operate at three-phase, 163 volts and 7.27 cycles.

The $CO_2$ system of fire protection is used, as well as a water sprinkler system.

### 13.8-Kv., 60-Cycle Bus

On account of the high ampere capacity of the main 230-kv. transformer banks, it was necessary to make the main buses of extremely heavy construction. Each consists of eight 4 in. by 1/4 in. copper bars arranged in a modified hollow square configuration.

All taps from the bus to the oil circuit breakers, bus potential transformers, and bus ground switches are made of copper bar. Considerable difficulty was experienced in securing a satisfactory design for connecting these taps to the bus due to the bus-bar arrangement and the restricted space; this was solved by placing a 90-deg. twist in the bus-bars where these taps were made.

In order to secure high-speed oil circuit breaker operation on the 230-kv. transformer banks, and at the same time obtain sufficient current carrying capacity, it was necessary to use two 3,000 ampere oil circuit breakers in parallel. To insure a satisfactory division of load between these two breakers, the copper connections were designed to tap the bus at one point, and from this point to run over equally dimensioned paths to the oil circuit breakers, from which point they again converge. The tap to the transformers was then made at a point equidistant between the two oil circuit breakers; the bus supports are of the 25 kv. class; all insulators are designed to withstand a stress of 6,000 lb. at the center of the clamp. They are spaced, on an average, about 4 ft. 4 in. apart. Flexible expansion joints are placed in the bus at intervals of approximately 50 ft.

The bus, and its connected equipment, is designed to operate ungrounded; therefore, the generator neutrals have been grounded only through potential transformers to which are connected ground indicators. The value of the isolated neutral lies in the fact that simultaneous grounds must be present on two phases before a short circuit can occur. It is hoped that the use of high insulation values and sensitive ground detectors will prevent the occurrence of this.

Isolated neutral operation has been practised successfully at Holtwood for over twenty years. At Safe Harbor, single-phase bus grounds encountered during the preliminary operating stage were cleared on two occasions without disturbance.

*Oil Circuit Breakers.* Oil circuit breakers are insulated for 25 kv. and are designed successfully to interrupt 1,500,000 kva. at 13.8 kv. They are cell mounted with each tank in an individual concrete cell. The mechanisms are located on the floor adjacent to each breaker.

The generator and 69-kv. transformer breakers are rated at 2,000 amperes, and have normal speed of operation. The 230-kv. transformer breakers are rated at 3,000 amperes (two are used in parallel) and have a guaranteed opening time from application of tripping current to clearing of arc of 8 cycles. The bus tie and bus section breakers are rated 4,000 amperes, and are designed to open at normal speed.

The oil circuit breakers are mechanically interlocked with their isolating disconnectors. Interlocking is further carried on throughout the high-voltage electrical areas where the Cory system is used to lock switches and bus doors on 13.8 kv., and switches on 69 kv. and 230 kv.

Special precautions were taken to isolate the oil circuit breakers at Safe Harbor. These breakers are located in separate rooms; in general, not more than four breakers in a room. $CO_2$ protection is provided for these rooms, and oil sumps below each breaker tank are drained to the tailrace.

*Disconnecting Switches.* All disconnecting switches are mounted on insulators interchangeable with those supporting the bus runs and taps. The disconnecting switches isolating the oil circuit breakers are designed so that the six poles are operated by one mechanism. When in the open position they are swung into ground clamps, thus isolating and grounding the breaker.

### 230-Kv. Transformers

There are at present two 230-kv. transformer banks. Each of these transformer banks has a normal self-cooled capacity of 84,000 kva., and a capacity with its blowers in operation, of 126,000 kva. One bank only is now complete with blowers; blowers are omitted on the second bank, as it is installed at present as an emergency spare bank.

The three single-phase units comprising each bank are located in individual cells, and are Y-connected on the 230-kv. side and delta-connected on the 13.8-kv. side. The high-voltage neutral is at present solidly grounded, but the installation is such that the banks may be grounded later through an impedor of such size as will hold the transformer neutral voltage below 76 kv. Four 2½ per cent taps are provided and located in the high tension winding; two above, and two below 230 kv.

These transformers are of the combined gas filled-conservator type in which a 16-in. nitrogen filled space, directly below the cover, is kept under positive pressure by the head of oil in a standard conservator. Expansion and contraction is taken care of by variation of the conservator oil level. They may be operated as standard conservator transformers, if desired.

The transformers are insulated to withstand an induced test of 461 kv. Their windings and bushings are designed to be coordinated with each other and with a 64-in. protective gap located on the high-tension structure directly adjacent to the transformers.

Each transformer is protected by a thyrite lightning arrester located on the power house roof adjacent to the transformers.

### 69-Kv. Transformers

There are at present two 69-kv., three-phase, 30,000-kva., self-cooled transformer banks, inertaire type, equipped with blowers to increase this rating to 45,000 kva. They are equipped for tap changing under load over a range of 10 per cent above and below 66 kv.

Each transformer is protected by an autovalve lightning arrester located on the roof close to the transformer leads. Protective gaps are not used at this voltage.

### 230-Kv. Substation

The tentative 230-kv. layout provides for double buses, with three breakers per position. The use of the so-called "breaker-and-a-half" scheme permits handling three transformer banks and five outgoing circuits with maximum flexibility and minimum space.

The initial installation in the 230-kv. substation is scheduled to coincide with the installation of the second 230-kv. line to Baltimore. This, however, is expected to consist of only a tie breaker, its isolating disconnectors, and line disconnectors. These will be so located as to fit into the ultimate design.

### 69-Kv. Substation

For this substation, it is proposed to use a double bus scheme, with selector breakers for each line and transformer. This substation will be adjacent to the 230-kv. substation and, for topographical reasons, one of the buses will be folded back upon itself. This actually has the advantage that it is possible, with the use of one bus section oil circuit breaker, to operate split high tension on three separate customers.

### 60-Cycle Substation Control

A common control room housing a complete switchboard and battery will be located at the substation site. Miniature control will be superimposed on this, and carried by means of telephone cables to the main switchboard room in the power house, so that it will be possible to perform switching operations from the power house normally, and in case of trouble from the substations directly.

### 25-Cycle Generators

These generators, which are proposed for unit spaces Nos. 1 and 2, will be rated 37,500 kva., 80 per cent power factor, 107.1 r.p.m., 13,300 volts, single-phase, 80 deg. cent. temperature rise on armature and field. They, also, will be of the overhung rotor design and will be equipped with direct connected main and pilot exciters. The closed system of ventilation will be employed.

The rotors will be equipped with heavy squirrel cage windings and the stators will be spring mounted to absorb the pulsating torque resulting from single-phase operation. These generators will probably be the largest 25-cycle, single-phase waterwheel units in this country.

Due to space limitations, it has been necessary to restrict the outside diameters to 30 ft. 8 in. This has resulted in an unusually high rotor design, and will require the introduction of air at both the top and bottom of the generator. Two sets of coolers are proposed on each end of these generators, each set being the same size and interchangeable with the sets on the existing 60-cycle units.

### FREQUENCY CHANGERS

The frequency changers will be of the horizontal shaft, four bearing type, designed to operate at 300 r.p.m. The generator will be spring mounted and will be rated at 25,000 kw., 80 per cent power factor, 13,300 volts, single-phase.

These frequency changers will be of the outdoor type. The closed system of ventilation will be employed, and the heat removed by the same type of surface air coolers as are employed on the vertical machines.

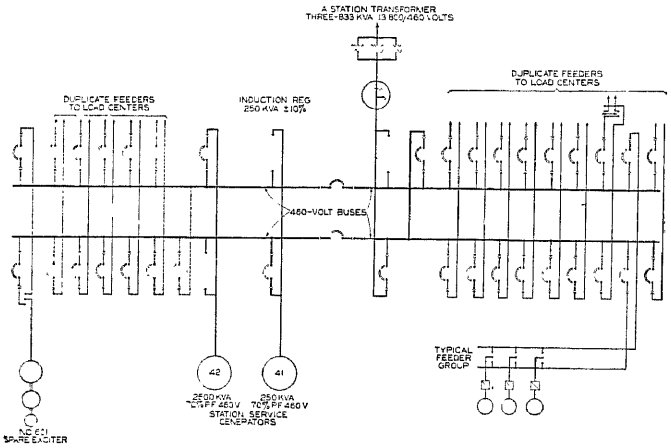
A STATION TRANSFORMER
THREE-833 KVA 13 800/460 VOLTS
DUPLICATE FEEDERS TO LOAD CENTERS
INDUCTION REG 250 KVA ±10%
DUPLICATE FEEDERS TO LOAD CENTERS
460-VOLT BUSES
TYPICAL FEEDER GROUP
42
41
2500 KVA 70% PF 460 V
250 KVA 70% PF 460 V
STATION SERVICE GENERATORS
NO 601 SPARE EXCITER

FIG. 11—SINGLE-LINE DIAGRAM, 460-VOLT STATION SERVICE BUS

Cable terminals, field rheostats, and auxiliary equipment will be housed in rooms built within the foundations below the machines.

### 460-VOLT AUXILIARY SYSTEM

The major auxiliaries at Safe Harbor are supplied at 460 volts from two 2,500-kva., 70 per cent power factor, 180 r.p.m., waterwheel driven, umbrella type house generators, and a single-phase transformer bank of 2,500 kva. capacity, stepping power from the main bus at 13,800 volts to 460 volts.

There are two station service buses, each of two sections, complete with section switches and one bus tie switch (Fig. 11).

Positions are available for connecting each of the house units and the transformer bank to either bus; truck type breakers are used; however, three trucks only are furnished at present for the six generator-transformer positions. Normally, one house unit is connected to each bus. The transformer bank is made available to one bus by placing its truck breaker in position on that bus. In case it is desired to transfer a house unit or transformer from one bus to the other, this can be done through the bus tie, or by actually transferring one of the other trucks to the empty selector position.

In general, duplicate feeders run from these buses to auxiliaries throughout the station. The more essential auxiliaries, such as governor pumps and spare exciter, are served by feeders having few auxiliaries on them. The more general auxiliaries are served from distribution groups, a number of which may be connected to a pair of feeders. The more essential feeders are connected to those sections of the bus supplied by the house units.

Each individual motor is equipped with an across-the-line starter rated at least 25 per cent in excess of the motor horsepower, and provided with thermal relays for overload protection. A safety switch is provided for feeder selection and isolation for maintenance, and this is fused as short circuit protection. The rupturing capacity of these fuses is normally ample on the system to which they are applied; however, they are backed up by the carbon circuit breakers on the feeders which have a rupturing capacity of 40,000 amperes.

The station service buses are isolated from each other. Each is contained in a steel structure, the two buses being separated by a 7 ft. aisle. A gantry crane spanning the aisle and supported from the steel bus structures is provided to facilitate handling of trucks.

Generators, transformer, tie and section breakers are of 4,000 amperes capacity. All feeder breakers are of the truck type. These switchboards are so interlocked that it is not normally possible for a man to get at live parts.

### EXCITATION SYSTEM

The unit system of excitation has been adopted, supplemented by a motor-driven spare exciter supplied from the station auxiliary system. Each of the main generators receives excitation from a 185-kw., 250-volt main exciter and pilot exciter, both mounted above and direct-connected to its generator. Provision is made for the future addition of a second spare exciter, if found necessary. A transfer bus and the necessary air circuit breakers are installed so that excitation for the main units may be obtained from either the direct-connected exciter or the spare exciter.

Generator main field rheostats are not required, as the generator voltage is controlled by varying the fields of the main exciters. The excitation system is designed for a moderately high rate of response of the order of 100 volts per second. Parallel fields on the main exciter are used to produce this value. An auxiliary field, on which the excitation may be reversed as desired, is provided in each exciter to take care of sudden major changes in voltage. The excitation of each unit is controlled by a high-speed voltage regulator.

### Lighting and Small Power System

Power for lighting and small auxiliaries is obtained from two 300 kva., three-phase, 460/208-120-volt transformers. Distribution is at 208 volts, three-phase for the smaller auxiliaries (motors 1 hp. and less). Lighting distribution is at 208-120 volts, three wire.

Exit lights and some of the control room lights are supplied direct from storage batteries. A number of bracket lights in the generator room and a percentage of the lights in the electrical bay can be transferred to the emergency lighting battery in case of failure of the a-c. supply; 32 volts, single-phase alternating current is used for wheel pit lighting.

Two 20-kva., 20-ampere series lighting transformers are installed for lighting the walkway on the dam and skimmer wall, the intake deck, the approaches to the power house, and the operators village.

### Control

In this station 250-volt control is employed. Duplicate batteries, each with an eight hour discharge rate of 95 amperes to 1.75 volts per cell, are provided. These are equipped with a tap to permit their use for auxiliary lighting at 250-125 volts, three wire. Normally, one battery is used for control, the other for emergency lighting and other miscellaneous d-c. requirements.

A 15-kw. charger is provided for the control battery. A 30-kw. charger, consisting of two generators driven by one motor, is used to equalize the charging on the lighting battery, and a 30-kw. single generator set is provided as a spare unit for both chargers. Switching and control for batteries and chargers, and switches for d-c. distribution are housed in a dead front steel switchboard.

D-c. distribution at the main switchboard is handled from duplicate control buses through dead front disconnecting fuses housed in distribution cabinets. These are located in the terminal room below the switchboard, there being one such cabinet for each piece of major electrical equipment.

### Main Ground System

The island in the center of the river offered an excellent location for ground electrodes, but it was a considerable distance from the power house. However, four ground mats, each consisting of approximately twenty rods connected to two 500,000-cir. mil cables by a network of 4/0 cable, were located on this island, and single lengths of 500,000-cir. mil cable, 300 ft. in length, were placed along the face of the dam. Inasmuch as this entire area is submerged, great care was taken to thoroughly braze all joints, and to break the network into a number of parts, the terminals of which were brought in through the face of the dam and connected together inside by two 500,000-cir. mil cables running through the inspection tunnel. The loss of one or more of these incoming feeders from the network should not seriously reduce the protective value of the ground.

In order to obtain a direct path for lightning arrester grounds, a number of 1,000,000-cir. mil cables were carried from the lightning arrester location on the roof, out into the forebay, and terminated in connections to heavy rail sections. These cables were connected to gate guides and other submerged metal passed on the way to the forebay. It is expected that the amount of contact surface offered will give a fairly low resistance.

At the shore end of the power house directly adjacent to the rock fill on the railroad is a section of quiet water. It is expected that considerable silting will take place at this point; therefore, a network of cables, with a backbone of 500,000-cir. mil feeders, is laid here.

Two 500,000-cir. mil cables join the ground mats on the island with those in the forebay and those in the shore end of the forebay. In addition, heavy 5-in. by ¼-in. copper buses in parallel with these cables connect all grounds in the power house area. From these heavy buses are run auxiliary grounds to all sections of the station. The transformer banks are directly connected by short loops to the cables from the lightning arresters to the forebay. This brings the transformer tanks and lightning arresters very close together electrically.

The transmission line ground wires are tied to the power house grounding system at several points in the vicinity of the power house.

### Communication

A Bell telephone system with a central exchange located in the control room is used for telephone communication throughout the power house. This is supplemented by an autocall system with stations located throughout the power house, dam, and substations, and by an operating order signal system between the switchboard and the turbine gage boards on the operating floor.

A system of telephone annunciator drops is used to advise the operating staff of unusual operating conditions. One large annunciator board in the control room covers all major machinery, while another of equal size is used to indicate operation of the $CO_2$ fire system, and, by thermostatic actuation, the location of fires in the electrical bay. Each unit gage board is equipped with an annunciator which shows the operations of the equipment connected with that unit.

### Relays

The main and house generators are equipped with differential relays which shut down the unit completely. They are, also, equipped with overspeed and overvoltage relays with contacts in series. These act to open the main and field breakers and shut the unit down to speed no load.

Provision is made for the installation of differential protection on the main buses; however, this protection is not yet installed.

The main transformer banks are equipped with differential relays, which protect a zone between the high-tension bushing current transformers and the low-tension bus. The 230-kv. transformers are, also, equipped with a high-tension winding differential scheme.

As each of the main transformer banks is connected directly to a line, line and transformer protection is somewhat correlated. High-speed impedance relays are used as protection against phase-to-phase faults. These are backed up by straight overload relays. Inasmuch as there are at present no high-tension buses on the system, ground protection is secured by the use of relays connected in the neutrals of the power transformers.

Counters are installed on the main annunciator board to record the number of operations of each of the main relays.

## TURBINES—MAIN UNITS

An outstanding feature of the plant is the Kaplan turbines, the blades of which are adjusted automatically as the load changes, to maintain high efficiency over a wide range of load; also, the relation between blade angle and gate opening can be varied manually to compensate for changes in head.

The turbines selected for this installation are of the Kaplan type, with automatically adjustable runner blades. The selection of this type of turbine followed an extensive investigation covering turbine units equipped with the four principal types of runners, namely, the Francis type, the propeller high-speed type with fixed blades, the propeller high-speed type with manually adjustable blades, and the Kaplan high-speed type, as selected for this project, with automatically adjustable blades. Typical horsepower efficiency characteristics for the Francis type, the fixed-blade propeller type, and the adjustable-blade propeller type runners are, in general, about as indicated by the curves shown in Fig. 12, under normal head operating conditions.

The investigation made covered various types and combinations of types of runners, too numerous to describe in this paper, but a general statement of the conclusions reached may be of interest.

The Francis type of runner, which in the past has been extensively used for operation under low and medium heads, was carefully investigated, but could not be justified for this installation, in view of the low power output in relation to the cost of the power house, and in view, also, of the high cost of the low-speed generator equipment required.

To overcome these objectionable features, the propeller type of runner with fixed blades was considered. The higher power capacity and higher speed of this type runner, together with its simplicity and low cost of construction, appeared to offer attractive possibilities. However, with the propeller fixed blade runner, the efficiencies drop off rapidly as the load is varied above or below the point of maximum efficiency and, as a result, inefficient use would be made of the water under such conditions.

Propeller type runners with manually adjustable blades were considered as a possible means for obtaining greater economy in the use of water and, although greater economy would actually be secured from this type of wheel with a fixed load on the station, and greater capacities would be obtained under reduced heads, no particular advantage would be gained under the varying load conditions which exist at Safe Harbor.

To eliminate the objection of poor economy under varying loads, an investigation was made of the use of one Kaplan unit with governor adjusted runner blades, in combination with five propeller fixed blade runner units. The horsepower-efficiency characteristic of the Kaplan runner is quite flat and, consequently, high efficiencies are maintained as the load on the unit is reduced. With such a combination of units, and with the propeller fixed-blade runner units all operating at best efficiency and the Kaplan unit taking the load swings, reasonably good economy in the use of water may be secured. The economical advantage of this combination of units over the combination of six propeller fixed blade runner units is indicated by the horsepower-quantity curves shown in Fig. 13. It will be seen that with this latter combination, the inefficient zones below the scalloped portions of the curves are very nearly eliminated, and the curve very closely approaches a straight line. With the introduction of the Kaplan unit, the economical performance in the use of water under both fixed and varying load conditions appeared very satisfactorily.

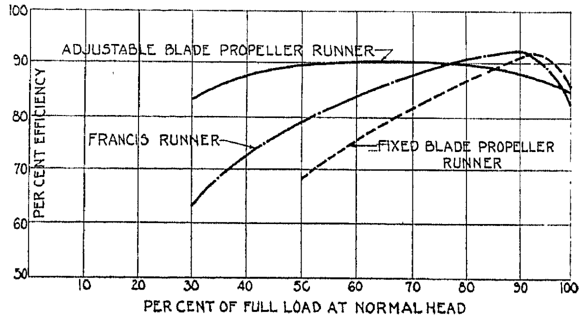

FIG. 12—POWER/EFFICIENCY-COMPARISON OF ADJUSTABLE BLADE, PROPELLER, AND FRANCIS TYPE TURBINES

It should be understood that Kaplan runners with their adjustable feature may be operated with the blades wider open than the fixed blade position on the propeller runner. Consequently, for a given wheel diameter, the Kaplan runner will have a higher maximum power, or, with the same power, a smaller runner diameter with a corresponding reduction in the spacing between units may be secured. The higher capacities are, of course, contingent on the runners being set sufficiently low for these capacities to fall within the power limits set by cavitation.

The curves in Fig. 12 were based on the various types of runners all having the same maximum power capacities and, consequently, the fixed blade propeller and the Francis runners are of greater diameter than the Kaplan runners.

The advantage in size of Kaplan units results in a smaller and less expensive power house structure and was an important reason for the final selection of six Kaplan adjustable-blade runner units, similar in size and design and having the same power ratings.

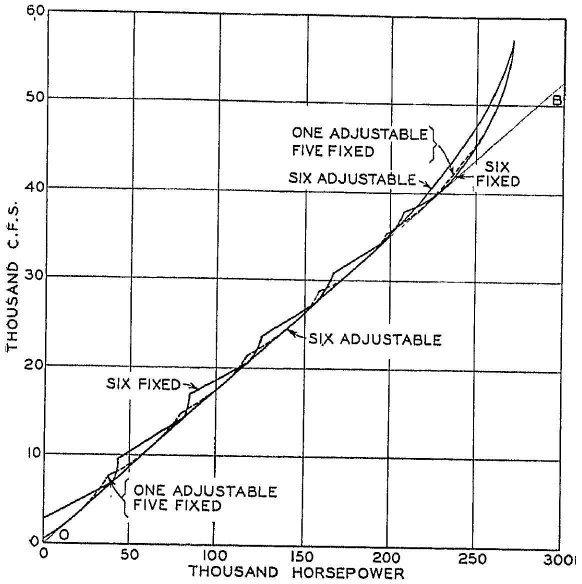

Fig. 13—Power Discharge Relation of Propeller and Adjustable Blade Turbines

Other advantages to be gained from the use of all Kaplan units, in place of other types and combinations of types, include the greater capacities obtainable with the adjustable blade in seasons of high flow, when the head is reduced below normal by a rise in tailwater level; convenience in operation, resulting from identical control features and performance characteristics, and interchangeability of parts, which makes possible the use of only one set of major spare parts for all units.

It may be of interest to know that for turbines of small size, the difference in first cost between Kaplan turbines and turbines with propeller fixed blade runners is appreciable, but as the turbine size increases the percentage difference becomes less, and for units of the size selected for Safe Harbor, becomes small and is practically negligible when considered in connection with the total cost of the development.

It may further be said that the units in this station are required to furnish energy over two separate systems, and it was decided that at least two Kaplan units should be installed for each system group, so that one will be available at all times for economical regulation of the load, should the other unit be shut down for inspection or repairs. On the basis of this requirement, it appeared that four Kaplan units should, in any case, be the minimum number considered. These are the highest powered Kaplan turbines in the world; the runners are 18 ft. 4 in. in diameter, and will discharge about 9,000 sec.-ft. at full gate and normal head. To minimize cavitation, these runners are set with their centerline 7 ft. below normal tailwater level. This location of the runners with relation to tailwater elevation was determined by exhaustive model tests in the Holtwood Hydraulic Laboratory of the Pennsylvania Water and Power Company, as described in a contemporary paper.*

Two means of unwatering the wheel casing have been provided. In the one scheme the tailwater can be lowered automatically by admitting compressed air to the wheel casings. As the gates on these units approach the no-load position, an air valve will open and admit compressed air to the wheel casing. If the gates are closed, as when running reserve, or as a synchronous condenser, air pressure will be maintained automatically in the wheel casing and depress the water level below the runner.

The alternative method of unwatering the turbines for inspection or maintenance is to put stoplogs in the discharge end of the draft tube and pump out the water with portable 10,000-gal. per min. unwatering pumps.

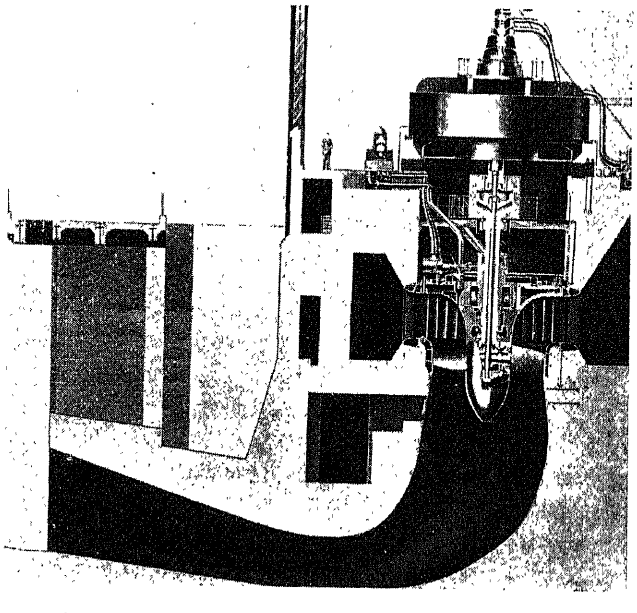

Fig. 14—Typical Section Through a Unit

The speed rings are of cast iron in four sections, containing a total of 20 stationary vanes cast integrally with the upper and lower rings. The overall diameter of the speed ring is approximately 28 ft. 10 in.

The speed ring and stationary speed ring vanes are cored hollow, and provision has been made for the introduction of steam inside the vanes as a protection against

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*Safe Harbor Kaplan Turbines*, by L. M. Davis and G. W. Spaulding.

the accumulation of frazil ice. Provision has also been made for the discharge of steam into the scroll cases, after these passages have been unwatered, to aid in dislodging any frazil ice which may have formed, and, also, to sterilize the wheel pits before men are permitted to carry on extended work therein.

The runner hub is normally submerged, and, for the lubrication and protection of the operating mechanism within the hub against corrosion, the hub is completely filled with a heavy grade of oil. The quantity of oil required for each runner is approximately 1,100 gals.

The turbine guide bearings are of the babbitt lined, oil lubricated type. One belt driven pump is used to circulate the oil in normal operation. A motor-driven pump, also, is installed to start automatically through the action of a flow meter, should the flow of lubricating oil in the supply line be reduced to the minimum quantity required for proper lubrication. These bearings are located below tailwater, and are protected by stuffing boxes.

Water leakage is discharged into the station sump well through two motor-driven pumps mounted on the turbine head covers, one of which is a spare pump. The spare pump is arranged to start automatically through the action of a float switch should the water in the space around the bearing rise to a dangerously high elevation.

The turbine operating mechanism consists of twenty movable cast steel gates actuated through two oil pressure cylinders connected to the gates through an operating ring and suitable links and levers. This mechanism is protected from injury by the use of shearing pins inserted through the upper and lower sections of the gate lever, one section of which is keyed to the gate stem. Fig. 14 is a typical section through a unit.

## GOVERNORS AND PUMPING SYSTEMS—MAIN UNITS

The governor equipment is required to perform the double function of regulating the speed and controlling the pitch of the runner blades. Consideration was given to the following features: degree of protection against outage of the units due to failure of any part of the governor system; sensitive regulation of speed; convenience in operation; space required.

Three types of governor systems were considered, namely; the unit system, providing for one governor and one pump operating separately with each main unit; the central system, providing for oil being furnished to all governors from a central battery of pumps; and the twin system, providing for the operation of two adjacent main units from one small central system located between the two units being served.

The twin system was adopted, and includes for each pair of units; two governors, two motor-driven pumps, two pairs of pressure tanks, and one sump tank with two compartments common to both units.

The governors are of the oil pressure actuator type with motor-driven flyballs. They are of light construction, a desirable characteristic for sensitive operation and quick response to changes in speed.

The pumps are of the herringbone gear type, motor driven. This equipment is so interconnected that one pump may be used for the operation of either one or both of the main units and the second pump held in reserve as a spare unit. Each pump is equipped with a pressure starting switch to provide for the automatic starting of the pump held in reserve should the pressure in the supply tanks fall below the minimum pressure limit setting for the first pump. Unloader valves are installed to permit continuous operation of these pumps, if desired, in which case the oil will be automatically by-passed to the sump tanks when no additional fluid is required in the pressure tanks. Should it at any time be found desirable to take either pair of pressure tanks out of service, the pipe connections are such that both main units may remain in service, with one on governor and the other on hand control.

With this arrangement of equipment, a high degree of protection against outage is obtained, as the two main units served by each system may continue to operate with any one piece of governor system equipment temporarily out of service. The pumping units are located on the main operating floor and can be served by the power house cranes. In addition, the pump motors have a separate source of supply from each of two station service buses.

Each governor is equipped with a safety shutdown torque motor and solenoid switch, to provide for automatic closure of the turbine gates to either the speed no-load or completely closed position through the operation of any one of a number of protective relays.

The characteristics of the torque motor are such that it will not permit the opening of the turbine gates beyond speed no-load position until the voltage has reached from 50 to 60 per cent of normal, at which voltage the flyballs will assume control, except by hand through the release of a mechanical lifter. It is designed, also, to prevent the gates from opening when starting up should one phase of the three-phase governor flyball motor circuit be open. After the motor has been placed in service, the gates will be automatically closed when voltage drops to approximately 40 per cent of normal, but will remain open, with one of the three phases of the governor supply open, should the voltage remain approximately normal.

The governor flyball motors are connected to the pilot exciters on the main unit shafts through slip rings, and operate at 163 volts, 7.27 cycles.

A unit may be quickly shifted from governor to hand control, or vice versa, by the throw of a single lever.

As these units are of the adjustable-runner blade type, the capacity of the pumps and tanks is more than double the capacities required for fixed-blade turbines of the same power and head. The capacity required for operation of the turbine gates at the normal pressure of 200 lb. is 457,000 ft.-lb., and for the operation of the runner blades, 685,000 ft.-lb., making it necessary for the pumps and tanks to provide for a total operating capacity of 1,142,000 ft-lb. The pressure and discharge piping at each governor, as well as the piping from the runner blade control valve to the oil head at the top of the unit, is 10 in. in diameter. Each of the four pressure tanks in one twin system is 7 ft. in diameter and 12 ft. high.

Oil was selected as the governor pressure medium in preference to water, in order to eliminate corrosion; also, to reduce power requirements, wear, and valve friction.

The movement of the blades is accomplished through a piston, in the shaft cylinder, which is connected with the operating mechanism in the runner hub through a vertical rod within the turbine shaft. The piston is operated under oil pressure admitted to and discharged from the cylinder through two concentric pipes within the generator section of shaft. For every position of the turbine gates, the runner blades are moved to a corresponding position to develop the best turbine efficiencies through a wide range of load. The flow of oil to and from the shaft cylinder is controlled by a valve, which is connected through a cam to the turbine gate operating mechanism. The relation of the turbine gate openings to the position of the runner blades is allowed to remain fixed within approximately a 4 ft. variation in head. Beyond this range other cams, which may be quickly and conveniently shifted into position, are employed to insure reasonably high efficiencies under a wide variation of head.

## HOUSE UNITS

Located in the ultimate center of the station are two house turbines of the Francis type, rated at 3,100 hp. at 180 r.p.m. under a 55-ft. head. They possess no unusual features not mentioned in connection with the main turbines.

The turbine casings are of the steel plate lined scroll type. The draft tubes are of the straight conical type, lined with heavy plate steel in the vertical sections.

## GOVERNORS—SERVICE UNITS

The governors for these units are of the self-contained oil pressure type, with the gate operating cylinders mounted on the governor base; energy is taken from the pilot exciter for the motor driven flyballs. One pumping unit is provided with each governor mounted with its pressure and sump tank on a common baseplate. Normally each pumping unit will serve its own governor, but the equipment is interconnected and of sufficient capacity that one pump can satisfactorily operate both governors. In flexibility of service, the arrangement of governor drives and pumps for these units is similar to the twin system used for the main units.

## STATION AUXILIARIES

In general, the station auxiliaries are located at the shore end of the station; this was done primarily to reduce operating costs; due to the nature of the power house site, the space was available at relatively low cost. There is provided the usual complement of hydro station auxiliaries, and as they presented no unusual features, the principal auxiliaries will be described very briefly.

*Air-High Pressure System.* This is provided for charging the governor pressure tanks and for operating the generator brakes.

*Air-Low Pressure System.* This is installed to furnish air principally for pneumatic tools; depressing the level of the water in the draft tubes for synchronous condenser operation of the units; and the air bubbler ice protection system on the dam.

*Oil Purification System.* One central oil purification system, with two centrifuge separators provide for the purification of all oil. One centrifuge is used for transformer and circuit breaker oil; the other for the governor and lubricating oil.

*Raw Water Supply.* A 24-in. main, with two screened intakes taking water from the forebay, is installed to serve all raw water requirements. The principal demands for raw water are the generator air coolers and thrust bearings. Water is supplied, also, to each set of generator air coolers through an 8-in. line, taking the supply from the intake of that particular unit, as well as through connection to the raw water main.

*$CO_2$ Fire Protection System.* $CO_2$ gas was selected as the means of extinguishing fires in enclosed areas. A central system, with appurtenances, has been installed. This system is installed on the generators, oil circuit breakers, and in the oil storage and purifying rooms.

*Vacuum Cleaning System.* A central vacuum cleaning system affords a convenient method of cleaning the interior of the station. There is a total of 223 wall and floor valves located throughout the station, all being served by one vacuum cleaner unit, centrally located.

*Water Filtration Plant.* A small filtration plant is located within the power house building to serve the requirements of the station, as well as of the operators village nearby. This filter is of the rapid sand gravity type, with two 50-gal. per min. filter compartments.

*Heating and Ventilation.* The office end of the power station and the control rooms are steam heated by oil fired boilers in the shore end of the building. Two water tube type boilers are installed, each with a normal rating of 100 boiler hp. The capacity of one boiler is sufficient to carry the normal heating load. The overload rating of the boilers, however, is such that an ample supply of steam will be available for steaming the turbine units for the removal of frazil ice.

The heating of the generator room is accomplished by the use of heated air, bled from the generators through louvers in the housing. The electrical bay is heated by the same air, distributed through a series of fans and air ducts to and from the various compartments.

## GENERAL

Application for a license was made to the Federal Power Commission on October 9, 1929, and was granted on April 22, 1930. Application for a certificate of Public Convenience was made to the Public Service Commission of Pennsylvania on January 10, 1930; this was granted March 31, 1930. Application was made to the Water and Power Resources Board for a Limited Power Permit on October 14, 1929, which was granted January 22, 1930.

The delivery of power to Baltimore from the first unit began December 7, 1931, 20 months and 7 days after active work was started on the project site—an outstanding achievement in the annals of hydroelectric construction. The drought that prevailed during the construction period and the absence of high floods were important contributory factors to the speed with which the work was executed.

In the average year, the Safe Harbor plant will generate over 800,000,000 kw-hr.

The design and engineering, acquisition of property, and negotiations with regulatory authorities were carried out entirely by the company's organization. The dam, power house, and relocation of the C. & P.D. Railroad were constructed under contract. The power company's construction organization installed all power plant equipment.

## ACKNOWLEDGMENT

The author desires to express his appreciation to his associates for the assistance rendered in compiling the material contained in this paper.

## Discussion

**J. R. Baker:** Probably the feature of advanced design most apparent to a reader of the paper is the use of the Kaplan turbine. However, the advantages secured by its adoption are not the only results of the progress in hydroelectric design that have occurred in recent years. A comparison of the cross-section, Fig. 6, with one of the Holtwood plant, located 7 miles below Safe Harbor and designed some twenty years earlier, will show a striking economy of building volume in the design of the Safe Harbor plant. In addition to an actual conservation of volume, the building mass and structure are applied to better purpose by more skillful arrangement. The great advance in hydraulic design is well illustrated by the fact that the controlled water path through the Safe Harbor plant is twice as long horizontally as that in the Holtwood plant, notwithstanding the smaller dimensions of the Safe Harbor plant. The operating heads are equal at the two plants. The dimensions referred to are as follows:

| | Safe Harbor Plant | Holtwood Plant |
|---|---|---|
| | Feet | Feet |
| Upstream face to downstream face | 187-11½ in. | 196 |
| Width of space under roof | 105 | 175 |
| Screens to outlet of draft tube | 168 | 85 |
| Center line of units to outlet of draft tube | 72 | 38 |
| Longitudinal spacing of units | 62 | 42 |
| Horsepower of units | 42,500 | 13,500 to 20,000 |

The designers of the plant undoubtedly considered the omission of a superstructure over the generators, and it would be of interest to know the reasons that lead to an inclosed generator room.

**P. M. Hess:** Safe Harbor today has been in operation for a little over 10 months. In connection with the papers presented it may be of interest to outline briefly the operating experience, good and bad, so far obtained with the major pieces of equipment.

### ELECTRICAL EQUIPMENT

The 230,000-volt transmission line, approximately 70 miles in length, has gone through a normal lightning season and an abnormal winter storm with an excellent record, having not a single outage or disturbance. Since all of the 66- and 70-kv lines sometime during the season had momentary outages due to lightning, this confirms the experience obtained on other 230-kv lines built in recent years: that well designed lines of this voltage are distinctly superior in this respect to lower voltage lines. During the severe sleet, snow, and wind storm of March 6th, 1932 when circuits of all natures were out, and in many cases on the ground, this 230,000-volt circuit rode through without any trouble.

On each end of this line are single-phase transformer banks of 126,000-kva capacity built by two different manufacturers, both of which have had a very successful record and very small maintenance. At the Baltimore end of the circuit a spare phase is provided while at the Safe Harbor end, a complete spare bank has been provided.

The Safe Harbor main 13-kv bus installed in duplicate, capable of being tied and sectionalized, is operated ungrounded, the same as the Holtwood bus. Operating ungrounded on this bus has probably eliminated two disturbances or failures during the early operating period because in two cases rats were found electrocuted by the capacity current to ground, which was of sufficient magnitude to burn the rats severely and slightly damage the bus insulators, but did not sustain any arc. Indications of grounds on this bus are obtained by lights in the control room, which are operated from the secondary potential transformers, connected between the generator neutrals and ground.

High-speed voltage regulators are installed on all of the generators, including the station service units, and have to this date functioned satisfactorily, without reflecting any at present noted speed change to the governor fly balls due to phase shifting in the pilot exciters. However, on the station service units, very sudden voltage digs are periodically received on the service bus by motors of from 100 to 200 horsepower being thrown directly on the station service bus. This inrush current is of such a short duration that the regulator scarcely has time enough to function before the condition is rectified. Investigations are at present under way to determine some means of correcting this somewhat annoying dip in station service voltage.

Circuit breakers, 460-volt truck type 4,000 ampere, are installed on the main 460-volt bus for generator and transformer sectionalizing and tying purposes in place of the customary oil circuit breakers. There have been several cases when these breakers have had occasion to function and they have given no difficulty.

The telemeter type wattmeter installed on the main generators for transmitting purposes has given no trouble with the exception of the sockets originally supplied for holding the automobile type head lamps, supplying the necessary spot light. These sockets have been replaced with ones of a more conservative current carrying capacity and, by a slight reduction in the lamp voltage, have since given no trouble.

The elaborate annunciator system in the plant has not been in service long enough to present any definite information on its reliability. However, some difficulty has been experienced with short lamp life and difficulty to obtain lamps of equal brilliancy.

### Generators and Turbines

The generators themselves have behaved entirely satisfactorily. There have been failures of the combined generator and turbine thrust bearings three times on two of the units; in each case occurring during starting operations. The cause of these failures is not entirely clear. It is *our* opinion that they should be tied in with the peculiar starting characteristics of Kaplan turbines. When running at synchronous speed the hydraulic thrust on a Kaplan unit is a minimum at no load and a maximum at heavy load. During the starting period, however, the thrust load may reach values decidedly in excess of maximum running thrust that is at a time that the bearing is least able to stand the additional friction caused by the thrust. This fact is caused by the nearly horizontal position of the runner blades of the turbines during starts, and is different from the conditions existing in Francis turbines. It seems that this starting thrust is roughly proportional with the gate opening at which the unit starts. By making both the runner and shoes in the bearing exceptionally smooth a double purpose is therefore obtained; first, the starting friction itself is reduced; this means a smaller gate opening required to start; hence less hydraulic thrust, which again reduces the friction. At any rate this has been done and is believed to have remedied the condition as no failures have occurred after 51 starts on one of the units and 89 on the other since the last inspection.

The turbines at Safe Harbor are installed approximately six feet below the tailrace water level and it became necessary to provide some means for unwatering the draft tube quickly when condenser operation is required. This is accomplished by admitting compressed air to the turbine pit at a pressure necessary to blow the water below the Kaplan nose and maintain it at this level. Admission of the air is controlled by an automatic controller actuated by the closure of the turbine gates. The initial inrush of air is comparatively large but the make-up air, which is the result of turbine gate, packing gland and gate stuffing box leakage, is extremely small. So far this scheme has been comparatively satisfactory, although some slight improvements are contemplated.

Many hydraulic turbines of the nature as installed at Safe Harbor have a more or less common type of guide bearing, using lignum vitae or hard rubber, both water lubricated. The Safe Harbor units are equipped with an oil lubricated babbitt bearing and this has, to date, been very successful. On the station service units the rotation of the turbine provides the oil circulation, whereas, on the main units, a belt-driven oil pump is installed for normal operation and a motor-driven pump for starting and auxiliary purposes.

Directly beneath this oil lubricated turbine guide bearing is located the main turbine packing gland. Considerable difficulty was experienced with this packing originally, due to the pressure variations on the gland. The variation on this stuffing box is from approximately 10 inches of vacuum to 17 lb pressure, therefore requiring a very pliable packing, that is, one with yielding characteristics. The original packing contained lead wire insertions. However, this has since been supplemented with a braided packing thoroughly impregnated with graphite, which will probably be the solution.

After approximately six months of comparatively heavy loading on the turbines the blades show evidences of a slight amount of pitting. This is being followed up very closely and has been largely reduced by a slight amount of reshaping of the blades in the various sections where cavitation has been more active.

It is the characteristic of low head hydro plants to be capable of exceptionally quick starting. This holds good also for the Safe Harbor units. On one occasion, when the system frequency went slightly low, due to two small steam units falling out of step, three units were started and paralleled at Safe Harbor in a total elapsed time of four minutes, thus increasing the system capacity with about 84,000-kw capacity without any difficulty.

A small amount of oil leakage is occurring at the leather packing glands on the turbine blade shanks. However, on three of the units this is practically negligible, whereas, on the other unit, the leakage amounts to an appreciable figure. The reason for this abnormal oil leakage has been traced, supposedly, to the sticking of the gland follower. By a slight change in the design of the follower, having one solid ring in place of sections, this will probably be entirely eliminated.

### Dam and Other Appurtenant Equipment

The skimmer wall installed for the purpose of preventing the entrance of trash and cake ice to the power house section of the forebay has proved to be very effective, since no trash to date has entered this section. It is believed that since this wall was effective during the preliminary pond filling stages when the amount of trash is naturally excessive, that no trash trouble will be encountered in the future. It is true that with four units in operation the velocity through the wall is only one-third of that which will be encountered when the ultimate twelve units have been installed, but even with twelve units operating the velocity of the water through the submerged opening will be only 1.75 ft per sec, so no trouble of this nature is anticipated.

The first winter of operation was comparatively mild and no statement can be made at this time as to the effectiveness of the bubbler system installed on the dam to keep ice away from the skimmer wall and spillway gates. However, preliminary runs indicate that no trouble will be experienced along this line. An item of interest is the effectiveness of the regulating gates installed on the power house side of the dam, which are operated by mechanisms installed in the dam and remotely controlled from the control room. These gates were used extensively during the spring freshet and have been found to be very effective in maintaining a constant pond elevation by bridging over the discharge capacity gap between spill gates in any desired quantity. Some doubt was raised as to whether or not it was possible to throttle the spillway gates without damaging the bottom rubber seal. At least three or four of these gates were operated in this manner for comparatively long periods without the slightest indication of damage. These gates were held in the throttled position by the gantry cranes. However, one gate is provided with a latching mechanism to support the gate in steps of three feet and this feature has proved to be of material advantage in the regulation of spill water.

The turbine stationary vanes and pits have been equipped with a means for steaming in case of the presence of frazzle ice. Also, a boiler plant of very flexible capacity, has been installed to provide this steam. The installed capacity, according to tests will supply steam for approximately three units simultaneously. However, there has been no occasion to utilize this scheme. It is believed that the severity of frazzle ice runs formerly frequently present at the Holtwood plant, has been greatly reduced by the wiping out of the rapids above Safe Harbor. Safe Harbor should also be superior to the older Holtwood plant in this respect on account of the larger size of the units and the deeper intakes designed for low water velocities.

In general, all of the many schemes provided for making the operation of Safe Harbor comparatively easy, and with as few men as possible, have to date worked out satisfactorily.

The operating force consists of six men per shift, making a total of eighteen operators, with three additional men provided for sickness, vacations and days off relief. A comparatively small permanent electrical and mechanical maintenance force is maintained to cover routine inspection and repair work, making a total plant personnel of approximately thirty-five men, exclusive of the supervisory force.

**F. H. Hollister:** This paper as well as the others related to this subject bring out very forcibly the following:

1. The great improvement made in low head waterwheels since 1910 allowing now a much higher speed, lower total investment cost, and a higher average economy.
2. The great advantage to be gained by the modern interconnected system that permits output to be utilized at the off peak period when the stream flow is often ample for the total installed capacity of the hydro station, but in an isolated system would have load for perhaps not over 20 per cent of its generating capacity. *Without extensive interconnections* the full use of the kilowatt hours available cannot be made use of when there is ample water, and a water-power economically unattractive without the long interconnections becomes feasible with them.
3. The additional expense for the more efficient turbine is more than offset by the advantages to be gained, or in other words, the most efficient turbine makes the overall cost of power the cheapest.
4. The distinct advantages to be gained by laboratory tests under as near as practical to service conditions, from the standpoint of cavitation, stability, and efficiency.
5. From the very clear description of the electric system and the reasons given for many of the important elements, it is well brought out that the system has been designed to give a high degree of reliability.

The following comments are submitted:

*Flat Efficiency Curves.* It is interesting to note that in hydroelectric work it has been found of advantage to get a flat efficiency curve.

In the Chicago District it has been found in the last few years that better economies are obtained with steam turbines with flat economy curves giving high economy between 50 to 85 per cent maximum continuous load rather than with units having best economy at maximum load. Although at maximum load efficiency is less, the units are seldom run at such points, and when run at good economy at least 15 per cent reserve is always available.

*Necessity of Better Economy and Lower Investment Cost.* The improvement in steam-turbine and boiler room efficiencies made during the last ten years has made it imperative to improve the overall all day efficiency of the hydroelectric station or else greatly reduce the investment permissible in a low head hydro plant.

*Improvement in Steam Plant Efficiency.* In 1910 when the Holtwood plant went into operation the best economy in yearly operation of a steam turbine plant was about 23,000 Btu per net kilowatt hour. By 1922 that had been reduced to about 18,000 Btu, and equipment now available can produce a kilowatt hour for under 12,000 Btu.

*Advantages of Automatic Bus Protection.* The designers have very wisely made provision for installation of bus protection on the main busses, although this is not in operation initially. The excellent results obtained for some years on other systems by either differential bus protection or fault bus protection would seem to emphasize the advisability of putting one of these systems into operation on any station of the size of Safe Harbor when interconnected with other large stations. In two large stations that went into service and made good records before either of these protective methods had been tried out, either system when available would have later probably prevented a serious shutdown with resulting expensive damage, and it has been found advisable to install one method in the first case and the other method in the second, with satisfactory results. From the last five years' experience it seems advisable in any large generating station on a large interconnected system, in order to meet modern service requirements, to use one of the two types of bus protection, irrespective of whether the main busses are open, in masonry compartments of either adjacent or isolated phase, or whether the busses are of the metal-clad type.

**A. H. Hull:** While the paper gives a comprehensive description of the undertaking and its magnitude, there is a number of features on which comments suggest themselves, not in any spirit of criticism, but in order to bring out, at greater length, some of the considerations that led to the construction adopted.

The single-line diagram indicates that transformer banks are to be fed from the same 13.8-kv bus system. With two transmission system requirements to be met, this would appear to limit freedom of varying the generator voltage.

It is pointed out in the paper that the equipment assembly space, with the service and office space takes 136 feet in length. This is about 27 per cent of the length of the building occupied by the main units in the initial construction and about 17.5 per cent of the ultimate building.

It is interesting to note that at Safe Harbor the usual practise in the past with respect to cooling of generators and transformers has been reversed. Here the generators are water-cooled and the transformers are air-cooled and some definite advantages are gained. It would be of value to know the reasons for adoption of air-cooled transformers. In northern climates, where temperatures drop to 30 deg and even 40 deg F below zero, water-cooled transformers are in successful use.

Would the author indicate the main reasons for adoption of the "overhung" type of generator and show what reduction in building height was secured as compared with that required for the type with thrust bearing above the rotor. Accessibility of the thrust bearing when located above the rotor has been advocated by some operating engineers as a sufficient reason for not adopting the overhung type of machine.

While use of the pilot exciter for furnishing energy for the motor of the governor fly-balls is attractive, and has been successfully used, there is one case where it was not proved acceptable since any operation disturbing the excitation system reflected into the governor system and caused surging. This particular installation used an 8-pole 250-volt exciter operating at 100 rpm with a two-pole motor on the governor head.

The use of two 3,000-ampere breakers in parallel on the low voltage side of the 230-kv transformer bank is an effective scheme. It would be of interest to know if higher generator voltage, say, 22,000 to 26,000 volts, was considered.

Two separate low voltage windings on the transformers have been used in some plants to keep the ampere rating of the switching within reasonable values.

In connection with the generator fire protection adopted, what was the reason for installing the water system in addition to the $CO_2$ system?

Where the expansion joints are used on the 13.8-kv bus, how is the copper fastened to the insulators? The general practise, the writer believes, is to have a tight clamp at one insulator in a given section of bus while at the other insulators, a snug clamp which would allow the copper to slide and yet be tight enough to withstand the short-circuit stresses.

The method adopted for grounding the generator neutrals only through potential transformers has worked out very satisfactory in various plants and is to be recommended.

Was any provision made to ventilate the 13.2-kv oil switch rooms? The writer recalls one case where the room temperature dropped about 10-15 degrees after a simple ventilating system was installed.

In connection with the auxiliary service, it is noted that 460 volts was adopted. In a steam plant where the equipment is more or less concentrated, this voltage, in the opinion of the writer, may be justified. In a hydroelectric station, where the auxiliary equipment is much more disturbed and to greater distance, a higher voltage seems to be justified. Not only is there considerable saving in copper, but a more reliable service is obtained on account of the reduction of short circuit and the use of transformers reducing the auxiliary voltage, say, from 2,300 volts to 460-208-104 volts as required.

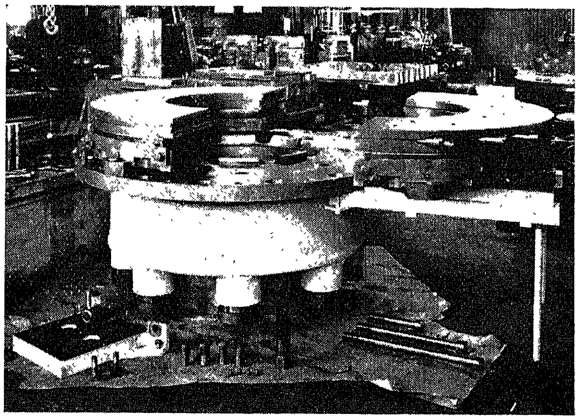

Fig. 1

Considerable study and expenditure has evidently been expended in connection with the main ground system, and it is well warranted. The writer recently installed a somewhat similar ground mat where the ground conditions were particularly bad, *i. e.*, mostly rock. A ground resistance was obtained of the order of one ohm. Would the author advise what ground resistance was obtained at Safe Harbor?

The writer wishes to acknowledge the assistance of Mr. T. R. Millar in preparing this discussion.

**Arthur B. Lakey:** The 82-in. pivoted segment thrust bearings at Safe Harbor carry a load up to about 1,500,000 lb apiece. The unit pressure on the 3,600 square inch net babbitted bearing shoe surface is accordingly 416 lb per square inch. The parts subject to possible damage in service, namely the tilting shoes and the runner plate, are interchangeable on all four units. The runner plate is split.

Speaking specifically of units Nos. 3 and 5, the shoes are positioned by a "shoe cage" ring. This part also is split. The only other large piece, the base ring, is a rigid non-split steel casting assembled semi-permanently with the generator bracket and contributing substantially to its strength and stiffness. The ring projects downward through and is supported by the bottom web of the bracket, by means of a flanged joint, gasketed for oil-tightness.

Each shoe is carried by a large tool-steel disk which in turn is supported on a thrust pin. It is at this contact point that the characteristic shoe-tilting takes place. Like most pivoted segment bearings previously installed in large American hydro-units, each shoe is carried by a large adjusting screw. Two thrust pins are interposed end to end between the shoe-support and the screw itself. The adjusting screws with their heads projecting in the clear beneath the thrust bracket, are almost down to the level of the Kaplan servo-motor coupling and hence easily accessible for adjustment at any time by removing the oil-tight caps shown. These caps have flats fitting the screw heads and are so designed as to serve as locks to preserve adjustment. This facility of adjustment without draining the oil bath is one feature of novelty on these bearings.

Another improvement giving added accessibility lies in the "shoe cage" above described. It is split at right angles to the two main bracket beams between which the bearing is placed. These beams form the two long sides of the rectangular oil pot. The closing sides are formed by two cross webs each having a door large enough to pass a shoe-cage half, complete with its four shoes and a runner half. Fig. 1 shows such a sub-assembly detached from the base ring and slid to one side. The parts are so designed that when the rotor weight is taken by jacks the shoe supports will slide off or on the thrust pins readily. A special buggy is provided which can be rolled against the oil pot door and receive the sub-assembly. The loaded buggy can then be dragged out clear of the unit. (The wooden structure shown in these figures was placed merely to represent the floor of the generator oil pot.)

Fig. 2 shows the long runner dowels which remain properly entered even if the generator shaft is lifted several inches to get at the Kaplan servo-motor.

In the foreground of Fig. 1 appears a cast shelf adapted to bolt on the side of the bearing. A shoe can be slid out on this ledge for inspection.

Five or ten years ago it was a common practise to build insulation directly into hydroelectric thrust bearings. Recently however, the tendency has often been to place full reliance on the insulation provided elsewhere in the generators. These bearings therefore were built without any insulation of their own.

To summarize, the novelty of this design consists mainly in the ease of vertical adjustment at any time, and the minimum disturbance of other parts of the unit incidental to inspecting or changing the bearing surfaces.

**Carroll F. Merriam:** In many respects the governing system at Safe Harbor represents a distinct advance in power plant design.

Contrary to former practise, the operation of the turbines has been concentrated on a single floor by the location of the pumps and actuators on the same level. This means a saving in personnel as well as avoiding the necessity of men tending pumps located below the main floor. The omission of half of a floor on the level with the top of the generators allows all of the governing equipment to be served by the main cranes, the accumulator tanks being reached through removable sections.

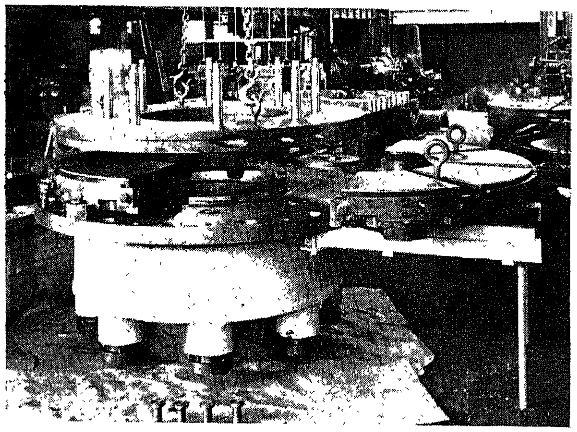

Fig. 2

An important feature is the compromise between the older central pumping plant and the later plan of separate complete governing systems for each unit. The twin system is really a central system for each group of two units, but because the whole can be located in the space between the two units of each pair, no long lines of piping are required. At the same time the interconnection between governors makes a considerable saving in spare pumping capacity that would be required in the unit system to prevent failure of a pump from crippling its turbine.

The pumps have been constructed on a special design to allow the oil to be brought to and taken from each pump through its base in order that quick replacement can be made simply by removing the anchor bolts which serve at the same time as flange bolts, and breaking the shaft coupling. On account of the readiness with which one pump can be interchanged with another, the requirements for spare capacity were again greatly reduced.

As far as possible, the length of the oil lines was held to a minimum particularly for the portions connecting the actuator with the accumulator tanks, the servo-motor cylinders, and the sump tank. The flow in these sections is intermittent with the movement of the gates, and so the inertia of the oil is a detriment to the quick response. The sump tanks were located directly under the pumps by taking advantage of the recess between the scroll cases. Consequently the suction lines are short, giving little friction loss to increase the lift, and the tanks are out of the way and do not occupy valuable space.

The fly-balls are motor-driven from the slip rings of the pilot exciter, and care has been taken to have little weight in the revolving parts in proportion to the power of the motor so that the speed response will be as prompt as possible.

From the electrical point of view, the protective devices, together with the annunciator system, are interesting. The general plan is that emergencies that may arise are divided into two classes, those requiring complete shut-down, and those requiring simply closing the gates to speed no-load position. Impulses received from the respective relays not only indicate the source of trouble, but also act upon one of the two safety devices arranged to produce the desired effect on the governor. The governor motor must be supplied with three-phase current with sufficient voltage to assure its starting before the gates can be opened beyond speed no-load position, except that provision is made that in case the break-away point at which the wheel starts to turn is higher, the gates may be opened but only when the operator is holding a special handle. In case of failure of one phase while the machine is running, the unit would not be shut down.

An interesting feature of the actuator itself is that provision has been made in the design for the eventual installation of several contemplated modifications after sufficient operating experience has been acquired to judge better regarding their desirability. In this respect there are interesting possibilities of improvement by simple substitution of a few special parts in place of the standard equipment.

**R. L. Thomas:** Characteristic features of large hydroelectric developments are their long incubation periods and the prolonged efforts expended in getting them started. Safe Harbor is no exception in this respect, but the project is perhaps unique in that long before it reached the actual development stage it fell into the hands of a strong operating company. Many of the flowage rights required for the development date back to 1902 when they were acquired by an individual, probably as a speculation. After changing hands several times they finally passed into the ownership of the Pennsylvania Water & Power Company, which was organized by Mr. J. E. Aldred, receiver of the McCall Ferry Power Company, which failed in 1907. The McCall Company had originally acquired some of the flowage rights above Safe Harbor for use by the Holtwood (formerly called the McCall Ferry) development, but in the final plans the crest of the Holtwood dam was lowered 20 feet. This left available for another development a fall of 55 to 57 feet from Columbia down to the Holtwood pond.

The Pennsylvania Water & Power Company from time to time, without any publicity and through its regular operating staff, made engineering and economic studies of the upper developments, the first preliminary design and cost estimates having been made in 1916. Additional key properties were also acquired through agents as particularly favorable opportunities arose. No outside services of any sort were employed prior to the making of core borings at the dam site and every effort was made to avoid any publicity. These methods resulted in relatively low costs of property and flowage rights and particularly of preliminary engineering and organization work. The prelicense cost of the Safe Harbor development, exclusive of property, amounts to less than 1 per cent of the total cost of the initial project. Other advantages of the Safe Harbor project are the small cost of railroad relocation work as compared with other developments on the lower Susquehanna, and the small amount of highway and bridge construction or reconstruction required.

The earliest engineering studies were for a dam located about one and one-half miles above the present site. At this location the river is narrower and the dam would have been shorter with considerably less volume of concrete. However, in order to utilize the fall of ten or twelve feet between the upper location and the Holtwood pool, it would have been necessary either to have carried out very extensive tailrace excavation at the upper development, or to have increased the height of the Holtwood dam by means of superimposed gates or movable dam. Furthermore there was no space available at the upper location for construction plant, camp, storage, etc. Exhaustive comparisons of several locations resulted in placing the dam just above the mouth of Conestoga Creek where the Safe Harbor turbines in effect discharge into the upper end of the Holtwood pool. The backwater effect in the Safe Harbor tail-bay varies roughly from one up to several feet, depending upon conditions of river flow, plant discharge and Holtwood flashboard installation.

It is now generally recognized that such "lapping" of heads is the economic method of developing water power sites in series on the same stream. Advantages are the reduction to a minimum of loss in head between plants; increase in amount of storage; and at least partial compensation for loss of head at the lower power house, in case of draw down of the lower pond, by gain in head at the upper plant by reason of the lowering of the tailwater.

**N. B. Higgins:** Mr. Baker's question respecting the omission of superstructure has been the subject of considerable discussion among hydroelectric power plant designers for a number of years. The reduction in cost that may have been effected through the omission of the superstructure was carefully studied before arriving at a decision. A number of factors were given consideration, which cannot easily be evaluated in money; such as, convenience of operation; delay, expense, and loss of service value due to adverse weather conditions; etc. The decision against the outdoor type of construction was not based on costs alone, but on careful consideration of all the factors involved.

A study of the power house cross-section, Fig. 6, will bring out some of the above points. The upstream wall is used for the low tension bus room, transformer pockets, control room, and station service bus room. The roof supports the lightning arresters, and, in part, the transmission line take-off structures. The enclosed generator room made it possible to carry on the installation of all units under cover at the same time. Without the superstructure, considerably more time would have been required for equipment installation (the first generator went into service 67 days after erection was started), with an appreciable expenditure for temporary housing. Some saving in first cost could have been shown, but when all factors were considered, the decision was in favor of enclosing the generator room. There is no doubt that other types of developments may justify the omission of the power house superstructure.

Mr. Hull has raised several interesting questions of design, to which the author replies as follows:

*Transmission System Voltage Control.* The transformer banks at Safe Harbor, supplying the 230-kv and 69-kv systems, are fed from the same 13.8-kv bus system. Busses are tied, or split, according to the system requirements. The connections are sufficiently flexible to permit operation of the 69-kv system in two sections, if necessary.

At times of system parallel operation, variations in the 69-kv transmission system voltage are met by tap changing under load on the 69-kv transformers at Safe Harbor and Holtwood; voltage control on the 230-kv system is obtained by the use of tap changing under load equipment on the 230-kv transformers at Westport, and by synchronous equipment.

The Safe Harbor generator voltage is normally operated at a relatively constant value; line drop compensation is not provided.

*Service Space Requirements.* Space requirements for general service rooms are unusually large, as it is expected that Safe Harbor will become the hub of an extended transmission line system of varying voltages and frequencies. Immediately adjoining the power house, there will be a substation for (ultimately) four 230-kv and six 69-kv, 60-cycle outgoing transmission lines, outdoor 60-cycle—25-cycle frequency changers, and a large 25-cycle, single-phase substation. The large number of transformers, oil circuit breakers, and related equipment thus depending upon power house facilities for assembly and maintenance, made it necessary to provide ample space for this purpose. There are included in this space, power house auxiliaries, water filtration plant, oil filtration plant and storage, boiler room, storeroom, shops, and operating, testing, and engineering offices.

*Transformer Cooling.* Both self-cooled and water-cooled transformers are employed in our Holtwood station. We have found the self-cooled transformers very much superior from the standpoint of maintenance and operation. Considerable difficulty has been experienced with the cooling coils in the Holtwood water-cooled units, on account of the suspended matter in the Susquehanna river water and the acid condition of this water at certain periods. At Holtwood it has been necessary to replace the cooling coils in practically every water-cooled transformer; there has been, also, one transformer breakdown and fire attributable entirely to failure of the water-cooling system.

At Safe Harbor, it would have been necessary to have installed an elaborate pumping and distribution system to handle the cooling water to the transformers as they are located above the forebay level.

For a number of years, water-cooled transformers were favored for hydroelectric stations on account of their relatively lower cost; this was obtained at the expense of lower efficiencies. An economic study comparing water-cooled, self-cooled, and self-cooled forced air transformers, with practically equal efficiencies, showed that in this installation the self-cooled forced air transformers offered the best possibilities.

With our present system of connections, *i. e.*, transformer-line unit, it is essential that each transformer bank have a heavy overload rating, so that the load can be picked up on one line with the other line out of service. The oil insulated forced air transformer is ideal for this purpose, giving high efficiencies at normal load, combined with high overload capacity, at low increase in cost for peak service.

*Use of "Overhung" Generator.* Lower cost and operating advantages led to the adoption of the overhung type of generator. The problem of bearing lubrication is very much simplified in the overhung rotor design, since there is but one guide bearing and this is contained in the same oil housing as the thrust bearing. It is believed that accessibility on this type of machine, with its direct-connected main and pilot exciters, and Kaplan head, is superior to an arrangement with the thrust bearing located above the rotor.

Special attention was paid to bearing layout in the design of the machines. On two of the machines, access to the bearing is at generator floor, through the cooler housings. On the other two machines, access is through the generator pit.

Eight of the units at Holtwood have their thrust bearings below the rotor. In eighteen years of operation, there has been but one failure, and that was due to an operator's error.

The height of the power house is based upon 25-cycle, single-phase generators to be installed in the future, and, is, therefore, more than necessary for the 60-cycle, three-phase generators. Preliminary designs of the manufacturers indicated that from 6 to 8 ft of headroom could be gained by placing the thrust bearing below the rotor with either type of generator.

*Pilot Exciter Supply for Governor Flyball Motors.* It is recognized that in several cases where the pilot exciter has been employed to furnish energy to the governor flyball motors, operation of the high speed excitation system produced phase shift and distortion of the main pole flux. This has caused the governor flyball motor to jump, and the governor system to surge. We believe that this source of trouble has been eliminated by using pilot exciters of ample size, and with compensating windings designed to offset the field distortion and phase shift.

*Use of Higher Generator Voltage.* The use of two separate low voltage windings on the 230-kv transformer banks was considered in the preliminary designs, but this would not have affected the ampere rating of the switches finally adopted, since two breakers would still have been required. We, also, studied thoroughly the use of 26,000 volts for generator voltage. This study indicated that the reduction in bus and switch gear cost was more than offset by the increase in cost, and decrease in efficiency of the generating equipment.

*Water Ring Fire Protection.* Inasmuch as water connections were readily available, it was decided to install water protection as a back-up to the $CO_2$ system, particularly when heat is being bled from louvers in the cooler housings to warm the generator room. In the first few months of operation, before the $CO_2$ system was completed, water was the only method of protection.

*Expansion of Bus.* The method described by Mr. Hull is employed at Safe Harbor for fastening bus copper to the insulators. The bus is clamped tightly at the center insulator, and the other insulators between expansion joints are given a clearance of a few thousandths; this permits the copper to slide, but at the same time is sufficiently tight to enable the bus to withstand mechanical stresses.

*Electrical Bay Ventilation.* There is equipment installed to ventilate the entire electrical bay, including the oil switch rooms, to eliminate condensation, for the removal of heat, and for the removal of smoke and gases in case of fire or electrical failure. The air circulated through the electrical bay is taken from the generator room through a set of forced draft fans, distributed into the oil switch rooms and bus rooms through a system of ducts, and exhausted by a set of induced draft fans. The capacity of the fans is such that for normal ventilation, six air changes per hour will take place in each room. In case of an emergency, such as a fire or electrical failure, the fans may be operated at double normal speed, and the smoke and gases may be quickly exhausted.

*Auxiliary Service Voltage.* In hydroelectric stations, a large number of the auxiliary motors are relatively small, and these are usually driven at an intermediate voltage of the order of 550, 440, or 220 volts. We do not believe, therefore, that 2,300 volts, with intermediate transformers, is justifiable, unless there is a number of large motors, such as motor-driven exciters, involved, or unless the structures are considerably scattered and very long feeders are required. We, therefore, selected 460 volts rather than 2,300 volts, or a combination of 2,300 and 460 volts, because of the reduction in space and operating advantages obtained by the elimination of oil-filled switching equipment and its replacement by air circuit breakers and standard industrial control.

Maintenance of air insulated equipment is more simple, and inspection considerably simplified and made more positive. Intermediate transformers were eliminated.

We doubt that a more reliable service is obtained at 2,300 volts on account of the reduction of short circuits. The protective devices employed at 460 volts are simple, positive, and in each case, we believe, adequate for the duty involved.

It is true that less copper is required for 2,300-volt distribution, but in a system where there is little utilization direct at this voltage, we believe that this advantage is offset by the additional stepdown transformers and equipment required for reduction to the intermediate voltage, and by the fact that considerable distribution is still required at 460 volts.

*Ground Resistance.* The ground system at Safe Harbor as measured at the time the station was placed in service was less than one-half ohm. It is expected that this value will decrease further with the accumulation of silt back of the dam.

# Reception and Distribution of Safe Harbor Energy in Baltimore

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***Synopsis.***—*This paper describes how the energy from the new Safe Harbor line is received in Baltimore and how it fits into the total energy supply of steam and hydro.*

*Safe Harbor energy being 60 cycles required a change in frequency from 62½ cycles and is tied in to the 25-cycle system by a 30,000-kw. frequency changer, the characteristics and control of which are described.*

*A bank of surge-proof transformers of 126,000-kva. capacity steps down Safe Harbor energy to 33 kv., handled in a new outdoor substation. This 33-kv. system ties in to both Westport and Gould St. generating stations and through them to the transmission system to Baltimore substations and surrounding territory.*

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PREVIOUS to 1910 the electrical demands in Baltimore were supplied entirely by steam generated energy. The first hydro energy received in Baltimore came from the Holtwood Hydro Generating Station on the Susquehanna River, the first generator beginning service in October, 1910. In 1911, four more generators began operation and by December 1914, eight 25-cycle generators were in service.

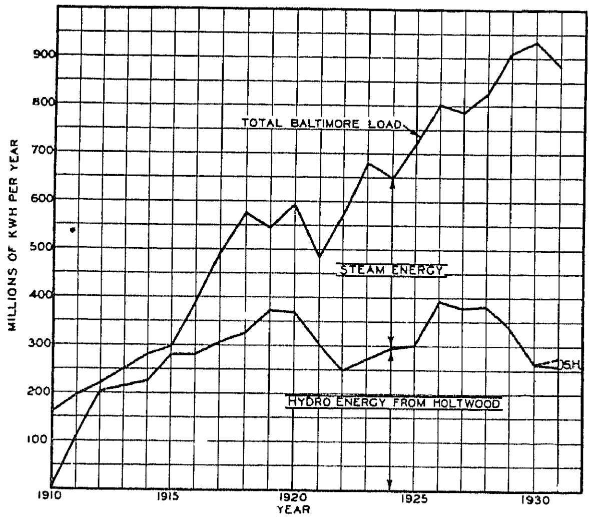

FIG. 1—USE OF HYDRO ENERGY FROM HOLTWOOD IN BALTIMORE SYSTEM

Fig. 1 shows the growth of total load in Baltimore since 1910 and also the hydro energy from Holtwood used in Baltimore. The curve indicates that Holtwood hydro was fully absorbed about the year 1919. Since that year hydro energy has been limited by the amount available, which in turn was governed by river flow and to a lesser extent by the amount of energy sold in Pennsylvania.

Energy from Safe Harbor was first received in December, 1931, and at once took an important place in the energy supply to Baltimore. Fig. 2 shows the amount of hydro energy received from Safe Harbor in the first six months of operation. The Holtwood hydro is superimposed over Safe Harbor hydro and the Baltimore steam makes up the total load. During the years to come, the Safe Harbor energy will doubtless be fully absorbed by the growth of load.

## STEAM AND HYDRO GENERATING CAPACITY

Table I gives the installed steam generating capacity in Baltimore and the installed hydro capacity in Holtwood and Safe Harbor and approximate capacity available in Baltimore.

TABLE I

| | Installed capacity (kw.) | | Approx. capacity available in Baltimore steam and hydro |
|---|---|---|---|
| | 25 cycles | 60 cycles | (25 and 60 cycles) |
| Westport (Steam) | 125,000 | 40,000 | 145,000 |
| Pratt St. (Steam) | 20,000 | | Reserve |
| Gould St. (Steam) | | 72,000 | 72,000 |
| Total Balto. (Steam) | 145,000 | 112,000 | 217,000 |
| Holtwood Hydro | 87,000 | 24,000 | 70,000 |
| Holtwood (Steam) | | 20,000 | |
| Safe Harbor Hydro (4 units) | | 112,000 | 108,000 |
| Total hydro | | | 178,000 |

## ELECTRIC LOAD IN BALTIMORE

The territory supplied by the Baltimore system is indicated by the map, Fig. 3. The northern boundary is the Pennsylvania line; eastern boundary the Susquehanna River and Chesapeake Bay; and the western boundary the two lines indicated. This area has a maximum breadth from east to west of about 50 miles and a maximum length from north to south of about 70 miles.

Baltimore has both 25- and 60-cycle loads; the maximum 25-cycle load recorded being 125,400 kw., the maximum 60-cycle load being 104,800 kw., and the maximum simultaneous load on both frequencies being 188,200 kw.

Twenty-five cycle frequency was originally chosen for industrial purposes and for the operation of rotary converters. Growth on this frequency has been held back in recent years in favor of the 60-cycle system.

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*Consolidated Gas Electric Light and Power Company of Baltimore.

*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

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### CHANGE OF FREQUENCY

Safe Harbor energy was first received in Baltimore on December 12, 1931, at a frequency of 62½ cycles to conform with the Baltimore system. On December 27 this frequency was changed to flat 60 cycles, at which time the older frequency changers were shut down. The sole 25- to 60-cycle frequency changer now operating is located at Westport and is capable of generating 30,000 kw. of either frequency. The old frequency of 62½ cycles was originally chosen to take advantage of the simple ratio of 4 and 10 poles on the 25 and 62½ cycle machines, the cost of such sets naturally being lower than sets with 10 and 24 poles respectively, as required by 25 to 60-cycle frequency.

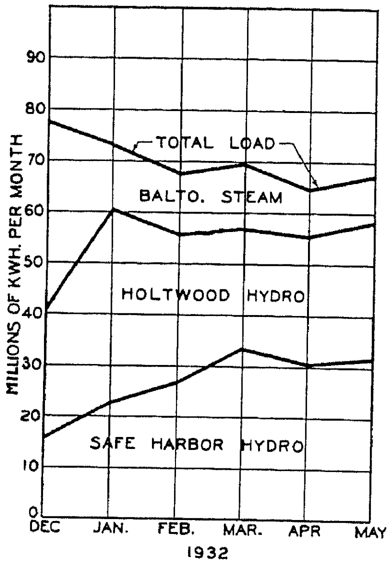

FIG. 2—SYSTEM OPERATION—HYDRO AND STEAM

### FREQUENCY CHANGER

Fig. 4 shows the load carried by the frequency changer for the first six months. The 60-cycle generation is plotted upward from the zero line and the 25-cycle generation downward from the same line, the ordinates between the two curves giving a total output in both directions which has amounted to about 8,000,000 kw-hr. per month. This machine forms a flexible tie between the 25- and 60-cycle systems enabling them to be run to some extent as a single system.

In view of the importance of this frequency changer in the operation of the Baltimore system it may be of interest to mention some of the characteristics of the machine and its control. The machine itself is shown in Fig. 5.

### POWER-FACTOR CORRECTION AND CONTROL

The 60-cycle generator has a full load capacity of 30,000 kva. at zero per cent power factor and the 25-cycle generator a capacity of 30,000 kva. at 70 per cent power factor. These capacities enable the machine to provide a substantial correction to power factor as may be needed on each system. The 25-cycle system carrying many rotary converters does not need as much correction as the 60-cycle system.

The desired voltage control of the set is obtained by the use of a separate exciter for each generator and a pilot exciter for each main exciter. A voltage regulator is supplied on the 60-cycle machine to provide for quick response regulation of the 60-cycle generator voltage. In addition to the regulator a so-called watt balance relay has been installed on both the 25-cycle and 60-cycle machines. The main purpose of these watt balance relays is to provide a means for automatically increasing the excitation upon the application of a heavy load to the frequency changer in order to increase the pull-out torque. The pull-out torque at rated voltage and full excitation is 62,500 kw. or over twice the normal rating of the machine. The main generator circuits are provided with oil circuit breakers but so relayed that they will open automatically only in the event of trouble within the machine windings. Otherwise they will remain closed to hold the 25- and 60-cycle systems together.

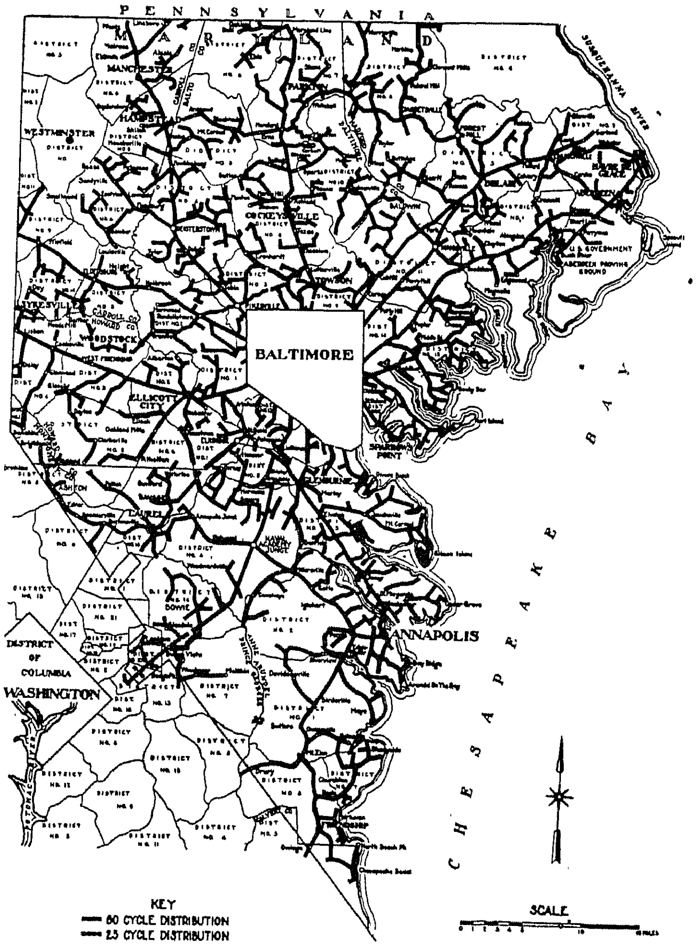

FIG. 3—ELECTRICAL DISTRIBUTION

Consolidated Gas Electric Light and Power Company of Baltimore and Annapolis and Chesapeake Bay Company

The full load efficiency of this set is 96.15 per cent and at ½ load 95.25 per cent. The resultant losses are less than one-third of the aggregate losses of the old frequency changers formerly operating in the substations. The saving in losses alone in the first five months of 1932 during operation of this single machine being 6,681,500 kw-hr.

### Mechanical Features

Both generators of the set are equipped with closed air circulation and each machine has two surface type coolers, tubed with Admiralty metal: 60,000 cu. ft. of air per minute circulate through each machine and its coolers. Harbor water is circulated through the tubes and as there are two coolers it is feasible to clean one cooler while the machine is running under reduced rating. This set has been operating about six months at this writing, from the inauguration of Safe Harbor service and has not been shut down during this time. The coolers are located in the foundation under the end-bells of each machine, making a compact and inconspicuous layout. On the 60-cycle machine a frame shifter is installed on the center line of the stator and between the coolers. This is operated by a motor driving worm and gear with links connecting to the stator. The operation of the set has been exceptionally smooth and there is comparatively little noise because of the enclosed construction.

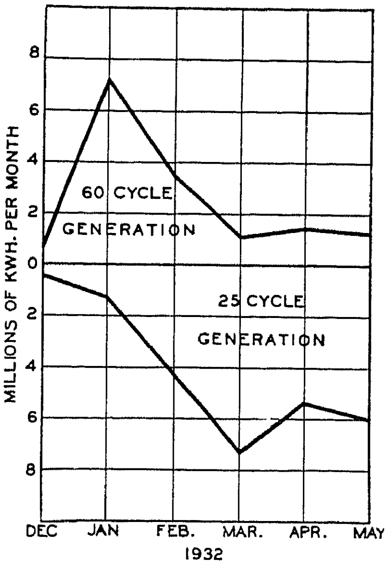

Fig. 4—Frequency Changer Operation

### Engineering Studies Preliminary to the Reception of Safe Harbor Energy

In making plans for the reception of Safe Harbor energy in Baltimore, it was necessary to make engineering studies, some of which were made in cooperation with the Pennsylvania Water and Power Co. Some of the more important of these studies are as follows:

The voltage of transmission to Baltimore.

The stability of the transmission system.

The location of terminal stations in Baltimore.

The kind and type of transformers used to step down.

The step-down voltage and intermediate transmission system.

The rearrangement of the Baltimore 13-kv. distribution cable system and the voltage regulation of the same.

The results of these studies are indicated by the equipment chosen as described in this paper, each decision arrived at being, as a rule, the result of a number of studies to determine the most economical, reliable, and otherwise satisfactory system and equipment.

### Transmission from Safe Harbor to Baltimore

This subject is fully covered in Mr. Hansson's paper submitted at this session. Suffice it to say that two transmission lines were decided upon; one terminating at Westport, our largest power station and center of distribution, and a second future line to terminate at Riverside, a property reserved for a future steam generating station. The transmission voltage of 230 kv. was found to give the necessary capacity with small line drop and also to give the greatest dependability by being as nearly as possible lightning-proof. The stability of this line proved, under mathematical analysis, to be entirely satisfactory. The 230-kv. potential was also best suited to possible future interconnection with other systems.

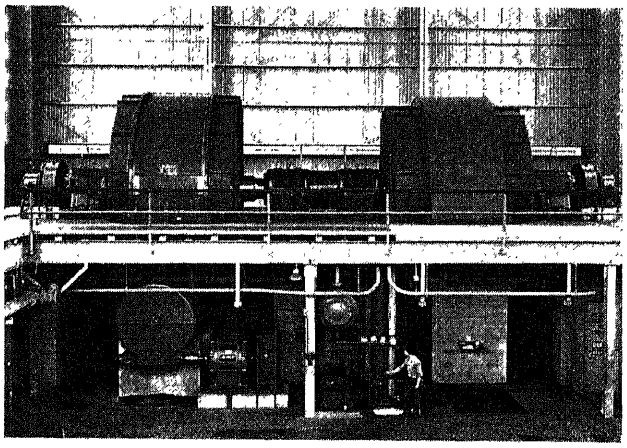

Fig. 5

### Baltimore Transmission and Distribution System

Fig. 6 is a single-line diagram indicating the main connections of the 60-cycle transmission and distribution systems. The present Safe Harbor line reaches Baltimore at Westport, at the west end of the system, and the future line will reach Baltimore at Riverside at the east end of the system. A large part of the energy stepped down at Westport is distributed through 13-kv. underground cables to various substations. It was necessary further to determine whether to step the Safe Harbor power down to 13 kv. directly or to use an intermediate bus of 33 kv. The latter plan was decided upon because the 33 kv. was more economical to transmit large blocks of power to the Gould St. Station, and in the future to the Riverside Generating Station and terminal of the second Safe Harbor transmission line. To step down directly to 13 kv. would also have overtaxed the capacity of the 13-kv. switches in our power stations, whereas by the use of an intermediate voltage and transformers the excessive concentration of power at 13 kv. has been avoided.

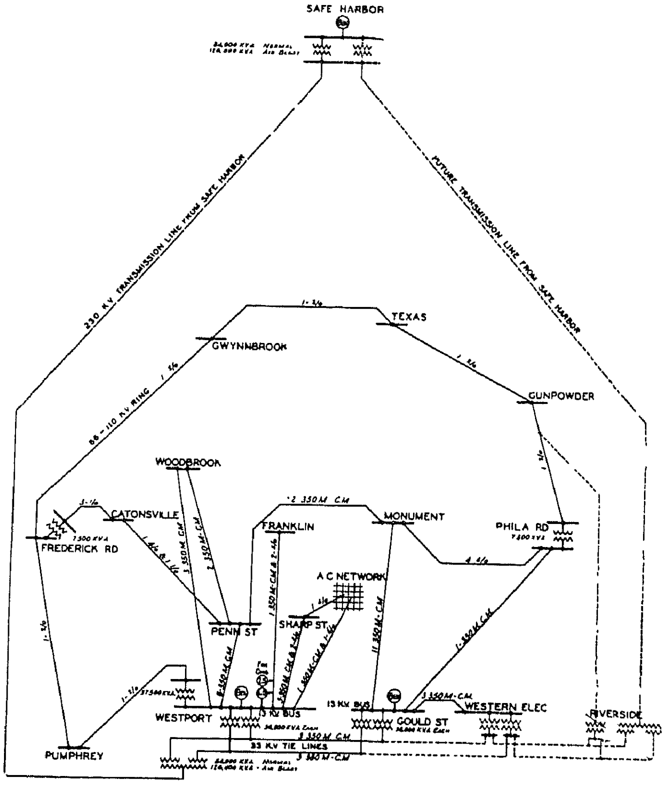

Fig. 6—60-Cycle Transmission System Baltimore and Vicinity

### Substation Connections

Fig. 7 gives a single-line diagram of the incoming line, step-down transformers and 33-kv. station. The secondary side of the transformer bank is controlled through two sets of buses at 33 kv. and delivers energy through four heavy connections of 36,000-kva. capacity each.

### 33-Kv. Ties Between Generating Stations

From the 33-kv. step-down station, shown on the diagram, two 36,000-kva. transmission ties are taken through oil-filled reactors and extend about 7,300 ft. to Gould St. About 2,240 ft. of this distance is a submarine section which crosses the Spring Gardens arm of the harbor near Westport.

Each tie consists of three 3-conductor cables of the shielded type with no belt insulation. The conductors are 350,000 cir. mils sector shaped insulated on the land cables with 26/64 in. paper and in the submarine section with 28/64 in. paper. The sheath is 5/32 in. lead and the submarine section is armored with No. 4 galvanized steel wire. The dielectric loss measured at the factory was 0.09 watts per foot in the three-phase cable when operating at rated voltage and at maximum safe operating temperature of 71 deg. cent. The power factor of the charging current was 7/10ths of one per cent.

The normal capacity of each cable is 12,000 kva. at 33 kv. or 36,000 kva. per tie circuit.

A General Electric oil reservoir is supplied at each joint and a pressure of 15 lb. per sq. in. maintained in these reservoirs. No failures to date have occurred in these cables over the period of 1½ years of service.

East of Gould St. twelve submarine cables have been laid across the channel from Fort McHenry to Lazaretto Point, with an average length of 2,130 ft. each. These cables were laid in a trench 47 ft. below mean low tide and covered with five feet of fill for protection. Only three of these cables are now operated for carrying load, but the remainder are designed to form a future tie from Gould St. through to the Riverside Station and second Safe Harbor line.

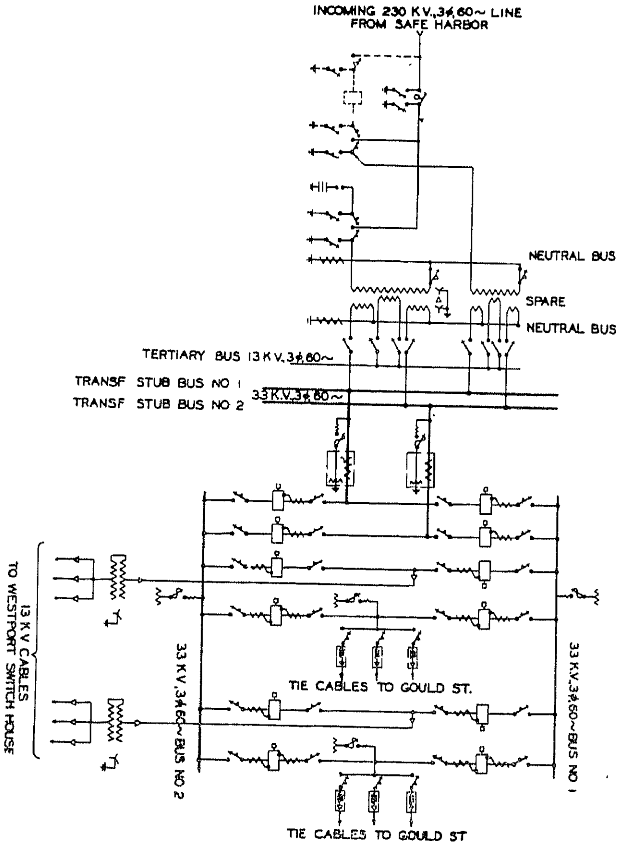

Fig. 7—Westport 230-Kv.—33-Kv. Substation

At Gould St. 33-kv. energy is stepped down to 13 kv. in two transformer banks shown in Fig. 8. These are auto transformers, three-phase, self-cooled, conservator type, 36,000 kva. each. They are equipped with tap changers to operate while carrying load, these tap changers being mounted in the box seen on the upper part of the transformer case. These transformers have a reactance of approximately 4 per cent.

### CABLE REACTORS

In Fig. 8 also, are seen the six cable reactors installed on the six 33-kv. tie cables from Westport. These reactors have a rating each of 456 kva., three-phase, at 60 cycles, 225 amperes per phase, 675-volt reactive drop, 55 deg. cent rise, for use on 34.5-kv. circuits. On this basis each coil will have a 3.38 per cent impedance drop at full load. This reactance is to limit the values of short circuits that may occur on the 33-kv. ties. The short-circuit guarantee of these reactors is 30 times full load for five seconds.

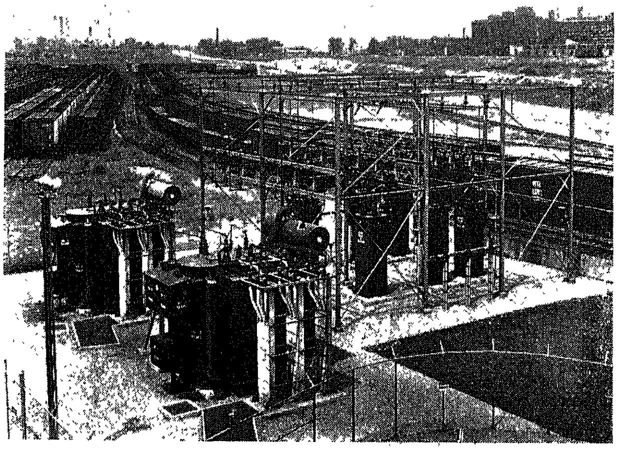

FIG. 8

### TRANSFORMERS CONNECTING TO WESTPORT SWITCH HOUSE

Two 36,000-kva. tie transformers similar to those described at Gould St. tie between the 33-kv. system and the 13-kv. Westport Switch House. The transformers are built with the necessary reactance to limit short-circuit current, while the cables to Gould St. are provided with special oil filled reactors. These four feeders total 144,000 kw. combined capacity which is sufficient to transmit the full capacity of the step-down transformers of 126,000 kw.

The Safe Harbor energy transmitted through the tie lines to Gould St. is distributed through 13-kv. cables, as shown in Fig. 6, to Monument St. and Philadelphia Road Substations. The 66-kv. ring around Baltimore is fed from the Westport 13-kv. bus through step-up transformers, as indicated.

### 25-CYCLE SYSTEM

Fig. 9 is a simplified diagram of the 25-cycle system connected, as previously stated, to the 60-cycle system through the 30,000-kva. frequency changer.

### STEP-DOWN SUBSTATION AT WESTPORT

Fig. 10 gives a general view of this station, showing railroad tracks in the foreground with siding to the transformer assembly house at the left. The incoming line from Safe Harbor is in the left center. This view also shows the oil storage tanks and oil filter house close by, with the four large transformers and the control house. Fig. 11 is a close-up of the 220-kv., 42,000-kva. transformers showing radiators with individual blowers. The rectangular metal tank on the side of each transformer contains switches and equipment for tap changing under load.

### MAIN TRANSFORMERS

The main transformer bank consists of four single-phase, 60-cycle, 28,000-kva., self-cooled shell type transformers, one of them being a spare unit. The radiators on each transformer are provided with small blowers which give an overload capacity of 50 per cent, or 42,000 kva. This air blast is controlled automatically from the transformer oil temperature and operated by mercoid switches which start and stop the fans automatically as required by the operating temperature. The spare transformer is connected so that it can be quickly switched in to replace any transformer that it is desired to disconnect. This operation takes from 8 to 10 minutes.

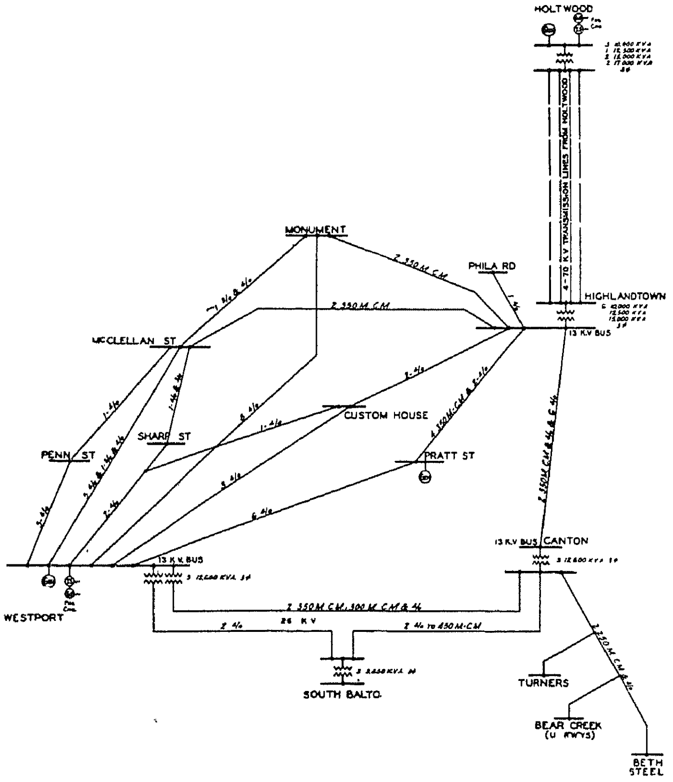

FIG. 9—25-CYCLE TRANSMISSION SYSTEM BALTIMORE AND VICINITY

Each transformer is provided with tap changers for operation under load so that the voltage of the system may be smoothly maintained over all load conditions. These taps are on the 230-kv. winding adjacent to the neutral point giving a voltage range of 20 per cent.

Each transformer has a tertiary winding, 9,800 kva. at 13,800 volts, delta connected. This winding aids in the stabilization of the system neutral and suppression of third harmonic voltages. The transformers are guaranteed to endure full short-circuit current for 5 seconds without damage.

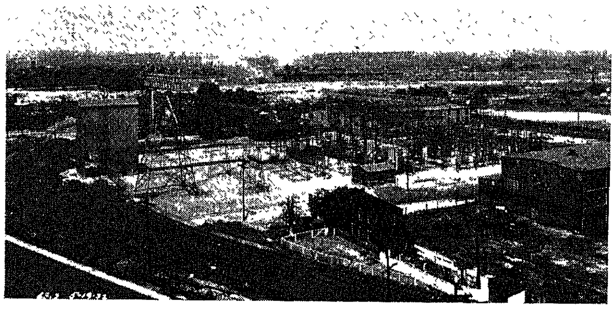

Fig. 10

There are two separate secondaries on each transformer of 33 kv., each of half capacity, so that the 33-kv. system is divided into two parts giving the equivalent of two banks of step-down transformers. This provision makes for reliability and reduces the magnitude of short-circuit currents.

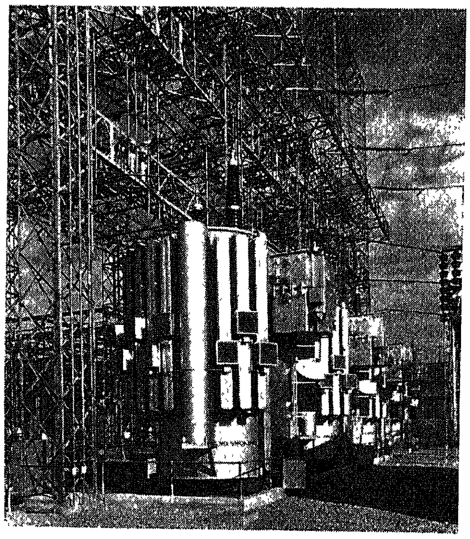

Fig. 11

Transformers are connected star-star with solidly grounded neutral. Transformers are supplied with condenser bushings including a potential device which operates neon lights and relays. Differential protection is provided for each of the three windings of each transformer so that failure in a winding will cause the transformer bank to be promptly cut out by automatic switch operation on the 33-kv. side. The 230-kv. side would be cleared by the overload tripping of switches at Safe Harbor.

These transformers were too large to ship completely assembled or to ship in oil. It was necessary to provide a transformer assembly house, shown in Fig. 12, equipped with a two motor lifting crane of 75 tons rated capacity. The transformer windings were shipped sealed in nitrogen to protect them from moisture. During assembly a blast of heated air was provided through the 6-in. gate at the bottom and when assembly was completed oil from tank cars was passed through a conditioning and drying machine into the transformer tank. Each transformer was moved from the transformer house over a wide gage track to a transfer car, shown in Fig. 13, which moves the transformer to its permanent berth. By this method any transformer can be promptly moved to the transformer assembly house where it can be opened, dismantled, or shipped.

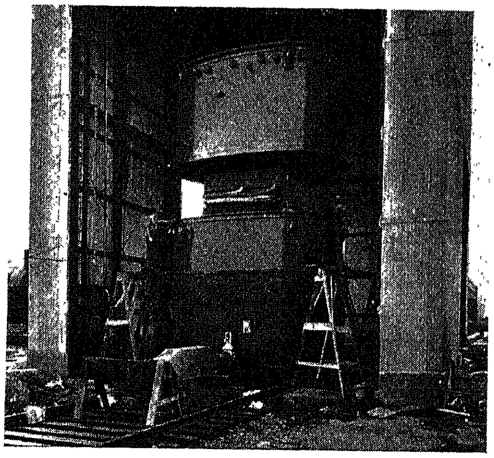

Fig. 12

The transformers are protected by the inertaire system to eliminate oxygen and moisture from the space above the oil.

## Surge-Proof Construction of Transformers

Much has been written concerning the surge-proof design of these transformers which were the first very large transformers to which this design was applied. The two outstanding features of the design are first, the proportioning of the high-tension coils to distribute electrostatic strain evenly over the winding and second, the boxing of each coil in insulation to eliminate creepage surface. It is unnecessary to repeat here what has appeared in the technical press. It is hoped that they are practically immune to lightning damage, having been subjected to an impulse voltage surge, on test, of 3 million volts without damage.

## Ground System

A ground system is provided consisting of a network of 1 million and 500,000-cir. mil stranded copper cables laid 3 ft. deep in the ground over the entire area of the 220-kv. and 33-kv. substations. Ninety-five ground rods have been provided driven 12 ft. deep. Connections between cables and rods are brazed to provide permanent low resistance connections. All steelwork, transformer tanks, switch tanks and metal structures are grounded to this network system.

## OIL STORAGE AND PUMPING

Two tanks are provided each holding 21,000 gallons—one for clean and one for dirty oil. These tanks are enameled inside to prevent contamination of the oil. In the oil house close by are provided pumps and a large capacity conditioning machine which filters and dries oil by a vacuum process and an auxiliary blotter process. Any transformer can be drained and filled while in its permanent location, the oil being handled through the equipment described

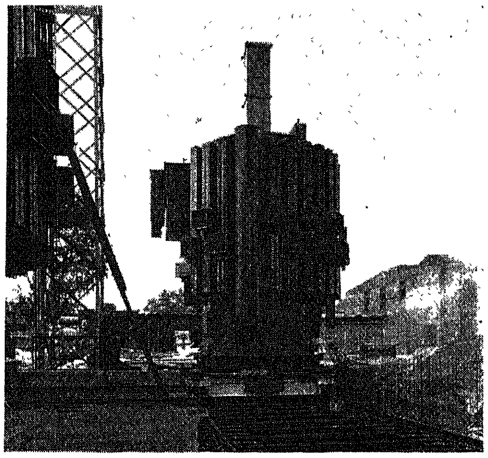

FIG. 13

## LIGHTNING ARRESTERS

Lightning arresters, shown in Fig. 14, are of the autovalve porous block type and are provided to relieve surges on the line. The upper part or gap section of the arrester is suspended from overhead steelwork through suitable insulators, the line connects to the top of the arrester, the upper section consisting of sphere gaps and the lower section of porous block elements. The normal rating of the arrester is 200 kv. but there is an additional section of elements normally short-circuited by a switch. If 25 per cent overvoltage occurs on the 33-kv. bus, this switch is opened, cutting in the additional elements and giving the arrester a rating of 240 kv. The purpose of this automatic device is to prevent discharge of the arrester in the event of overspeeding of the hydro generators at Safe Harbor.

Spill gaps are provided on each line with a 3-ft. diameter top ring, a 5-ft. diameter bottom ring, and a 64-in. gap to relieve a high-voltage surge in the event that the lightning arrester cannot dissipate the surge. These spill gaps will flash over before the transformer bushing flashes over and the transformer bushing will flash over before the transformer windings are injured.

The various elements of insulation in this station are coordinated, the breakdown strength beginning with the lowest strength as follows:

The lightning arrester, spill gap, transformer bushing, and finally the transformer itself.

The steelwork for both 230-kv. and 33-kv. stations is all galvanized. Disconnecting switches are mounted in direct line of high-voltage connections to transformers and operated from a convenient position on the ground.

The 230-kv. equipment is protected by five ground wires strung well overhead to continue the ground protection given to the transmission line.

## OIL CIRCUIT BREAKERS

No oil circuit breaker is provided on the 230-kv. coming line, although space is left for the same if it should be required when the second line is built from Safe Harbor. All the switching is done on the low side of the large transformer. These switches are rated at 34.5 kv., 1,200 amperes and have a rupturing capacity of 1½ million kva. Each three-phase switch is operated by solenoid and is guaranteed to clear the circuit in case of automatic trip in not more than 8 cycles. The contacts of the switches are of the deion type.

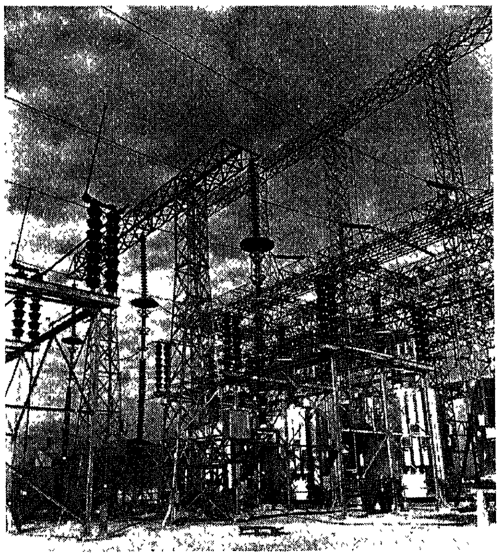

FIG. 14

## CONTROL HOUSE IN OUTDOOR STATION

The Westport Operating Room and Load Dispatcher's Room are about 900 circuit feet distance from the step-down station and this long run would have introduced too great a drop for current transformer circuits and control circuits connected in the usual manner. It would also have cost very much more than the method adopted which was the establishment of a control center in the outdoor station to serve as the terminal point of the secondaries of current and potential transformers and the control wires from oil circuit breakers and other equipment.

The control house contains storage battery and charging set; also switchboards for control switches, relays and meters. The control house forms one of two control points, the other being in the switchboard operating room, so that a dual control is furnished. Electrically operated equipments, such as oil circuit breakers, fans, lightning arresters, switches, etc., are controlled from the switchboard operating room through 16-conductor, No. 16 wire control cables, which operate relays in the control house and these relays close or open the d-c. circuits to the equipment.

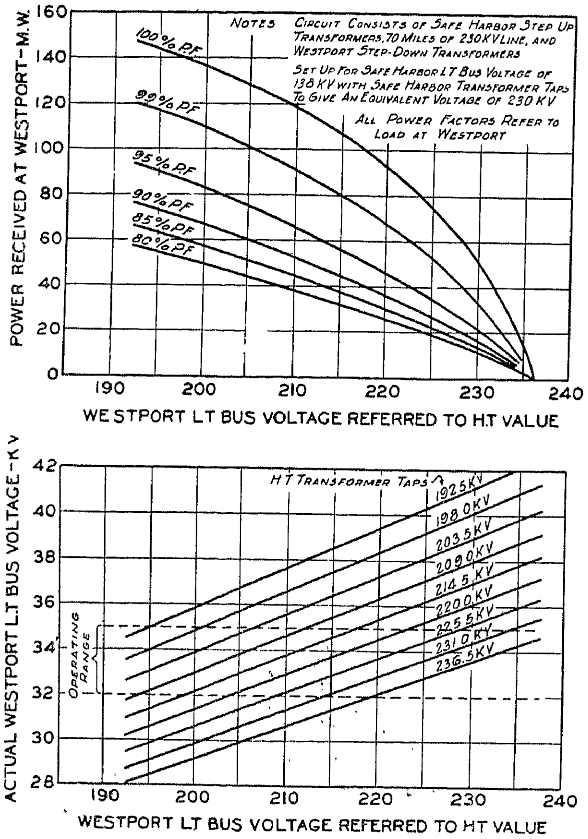

Fig. 15—Voltage Regulator Curves for Safe Harbor—Westport Circuit Used in the Determination of Westport Transformer Taps

The control house also contains standard instruments and meters for measuring the circuit outputs and in the control house are located special relays and totalizing instruments which pass on the principal indications to the switchboard operating room in the power house.

## Voltage Regulation of Baltimore Load

One fundamental requirement of the voltage regulation in Baltimore is to supply the 13-kv. customers with approximately constant voltage. Many of these customers are supplied by radial cables from substations, others by cables from generating stations. The practise has been, and is, to so regulate the 13-kv. buses at the Westport and Gould St. generating stations that the voltage at customers' premises should not vary materially. This means that at times of heavy load the generating station buses carry a higher voltage than at times of low load, the general values ranging from a minimum of 12.8 to a maximum of 14.2 kv. and the actual voltage of these buses at any time being that which will give the best average voltage to 13-kv. customers.

Another requirement of voltage regulation is the supply to the a-c. network in the central part of the city, which network is of recent construction. Our experience to date, indicates that a very uniform network voltage has been maintained by the same method of compensating for drop by increasing voltage at times of heavy load.

The company has a large 4,000-volt distribution load fed by radial feeders from substations. This does not introduce a regulation problem as each three-phase feeder is equipped with three single-phase regulators between phase lead and ground which provide excellent regulation at the feeder point.

To obtain satisfactory and easily controlled voltage it was decided to equip the 230-kv. step-down transformers with tap changing under-load equipment.

Fig. 15 shows a typical sheet of curves that were developed to determine the best ratio for step-down transformers and the proper taps for obtaining desired voltages under all load conditions and varying power factors.

Taking the normal generator voltage at Safe Harbor and taking one of the transformer taps at Safe Harbor the upper curves were laid out with ordinates of power received at Westport. The abscissas were Westport low-tension bus voltages referred to high-tension values in kilovolts. Actual voltage values were then calculated following Nesbit's "Electrical Characteristics of Transmission Circuits" and using Wilkinson's formula and the circle diagram. Such calculations were made for various power factors from 100 to 80 per cent. These curves give the terminal voltage at Westport for any load on the transmission line and any particular power factor. These curves show the regulation of the transmission line including the step-up bank at Safe Harbor and step-down bank at Westport. It is of interest to note the greatly increased amounts of power that can be transmitted at high power factor approaching unity for the same voltage drop.

In order to forecast actual Westport low-tension bus voltages the curves just below are developed with actual voltages as ordinates and the same abscissas as the upper curves. Each of these straight lines represents the conditions under one transformer tap, of which there are nine in all. The satisfactory range of voltage conditions lies between 32 and 35 kv. as indicated by the horizontal dotted lines in the figure.

The taps on the step-down transformers provide as above indicated control of the 33-kv. voltage. In tying from this system to the 13-kv. bus at Westport and at Gould St. generating stations and in the future at Riverside we do so through transformers of 36,000-kva. capacity, which are also provided with tap changers operated under load, which will enable the several generating station voltages to be adjusted as required to suit their individual transmission requirements.

## TESTS OF 230-KV. TRANSMISSION LINE

On completion of the Safe Harbor-Baltimore line and before the first generator was available at Safe Harbor tests were made, in cooperation with the engineers of the Pennsylvania Water and Power Co., from the Baltimore end to determine the electrical constants of the line for the purpose of analyzing and predicting its performance under normal and abnormal conditions. The measured values checked very closely with the calculated or theoretical values. A few of the interesting test results are as follows:

The insulation resistance of the three conductors to ground was in excess of 200 megohms indicating that there were no grounds on the line.

The d-c. resistance of each conductor at 25 deg. cent. was found to be 8.0 ohms. The a-c. 60-cycle resistance per conductor at 25 deg. cent. was found to be 8.7 ohms. The difference between the a-c. and d-c. resistance of 0.7 ohms is due principally to hysteresis and eddy currents or iron losses due to the steel core used in this aluminum conductor.

The d-c. resistance of the earth and ground wire return between Safe Harbor and Baltimore was found to be 0.55 ohms, this indicating a very low value of ground resistance at both ends of the line. The resistance of the two ground wires in parallel is about 16 ohms indicating that in this test very little current passed through the ground wires.

The effective 60-cycle a-c. resistance of the earth and ground wire return was found to be 6.43 ohms. This value is much greater than the d-c. resistance due to the relation of the leakage impedance of the line conductors and ground wires and the mutual impedance of the earth.

The balanced impedance per phase at 25 deg. cent. was found to be 59.7 ohms per conductor.

The zero phase sequence impedance was found to be 125.4 ohms. This value is three times the impedance measured by taking the three conductors in parallel with the return circuit through the earth and overhead ground wires. This value is of real importance in the calculation of ground faults and the solving of inductive coordination, and in figuring the stability of the line under various fault conditions. It is of interest to note that this value is 210.4 per cent of the balanced or so-called positive phase sequence impedance per phase.

The open-circuit line excitation at 60 cycles and 230 kv. required 51.1 amperes or 20,400 kva. This condenser effect is an important element in the control of power factor and line voltage. The high charging kva. of such a transmission line has the well-known result of increasing voltage on the generators for a given field current due to the boosting effect of armature reaction of currents at leading power factor. If the transmission line is excited by a single generator, this condenser effect may lead to excessive line voltages unless the field current is held to the necessary low value. The Safe Harbor generators are designed with this in view but in exciting the line from the Baltimore generators the excitation must be controlled to the desired low value.

# Low-Head Hydroelectric Developments

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**Synopsis.**—*In the last few years very rapid progress has been made abroad in developing the theory of low-head developments and this has resulted in a wider use of Kaplan turbines. Every engineer interested in the design of low-head developments should familiarize himself with at least the principles of this theoretical work and its practical application.*

*The paper gives a general outline of the present situation which seems to have been somewhat neglected in the United States. Starting with general ideas about Francis, propeller, and Kaplan turbines in low-head developments, the important points are discussed with respect to cavitation and pitting, modern design theories, design of propeller and Kaplan turbines and the research requirements and practise. Next the practical application of the theories are demonstrated by a table of designs executed or projected, and finally, some of the tendencies in extending the use of Kaplan turbines for higher and much lower heads are discussed.*

THE design of an up-to-date low-head hydro-power plant requires a thorough understanding of the ideas and theories that have originated within the past few years in connection with such developments. The present paper is a continuation of a paper† delivered by the author at the 1930 Summer Convention of the Institute, and reviews the latest theoretical and practical work and discusses the modern trend in the design of low-head plants.

In the eastern part of the States, and to a greater extent in Europe, the number of power sites that can be developed economically by the use of conservative Francis turbines is rapidly diminishing. Many of the remaining low-head sites can be developed only by the use of more economical methods, *i. e.*, by turbines of the propeller and particularly the Kaplan type.

It took about twenty years to develop the mere ideas of Professor Victor Kaplan. This work started with small models of the propeller and Kaplan turbines, followed by commercial sized machines, the first of which, a 40-hp. unit, was put into operation in 1919, and finally in 1930 reached the size of 38,000 hp. in the Ryburg-Schworstadt units, and in 1931 of 42,000 hp. units in the Safe Harbor plant.

In so far as physical size is concerned, the Ryburg-Schworstadt turbines were the largest built, and the year 1930, when these turbines were put into successful operation, can be considered as the turning point. Today, however, Kaplan turbines are under construction, which are even larger in capacity and physical size than the Ryburg-Schworstadt units; this could have been accomplished only by the most efficient collaboration between theory and research and their practical application. The credit for this past accomplishment was due entirely to European engineers, who developed remarkably close cooperation between all interested parties, coupled with an amazing amount of work.

The conditions in the States were unsatisfactory and the turbine manufacturers were unable to make the model tests so essential to the development and proper design of Kaplan and propeller turbines. Consequently, when the Safe Harbor development was undertaken, the operating company had to build and operate its own cavitation laboratory in order to secure the necessary information from model tests.

## FRANCIS, PROPELLER, AND KAPLAN TURBINES IN LOW-HEAD DEVELOPMENTS

Large low-head developments require the handling of very large volumes of water. In many cases, neither effective storage nor regulation can be obtained economically. Not only does the amount of available water vary but the turbines must be operated under a varying head and these variations are relatively much larger than in medium or high-head developments. Hence the economy of low-head developments depends on the ability to handle at low cost and at high efficiency these large and varying volumes of water at varying heads.

The convenient criterion for comparing different turbines is the so-called specific speed which represents the number of revolutions per minute that a homologous model runner must make to develop one unit of power at one unit of head. In English units this means a comparison of models that will develop one horse power at one foot of head.

At the same head and output the number of revolutions of different turbines is directly proportional to the ratio of their specific speeds, and for turbines of similar design the diameters of the runners are in inverse proportion to the ratio of the square roots of their specific speeds.

For Francis turbines an increase in specific speed is accompanied by a decrease of efficiency, due to the increased friction and eddy losses.

The original Francis turbines had proper specific speed for medium heads but for low or high heads their specific speeds were unsatisfactory. Consequently, to make such turbines more suitable for such heads, they must be modified to lower the specific speed for high heads and increase it for low heads.

Considering that the amount of space required for a unit, and hence the size of the sub and super-structure,

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†*Present Day Hydro Power Practise in Central Europe*, by A. V. Karpov, A.I.E.E. TRANS., Vol. 49, No. 4, p. 1642.

*Presented at the Middle Eastern District Meeting of the A.I.E.E., Baltimore, Md., October 10-13, 1932.*

depends on the diameter of the runner, and also that the size and cost of the generator diminishes rapidly with an increase in specific speed, the important economical influence of the change from lower to higher specific speed runners can be seen clearly. For rough approximations it can be stated that the initial cost of the power-house, including the hydroelectric machinery, for low-head developments, is approximately in inverse ratio to the three halves power of the specific speed.

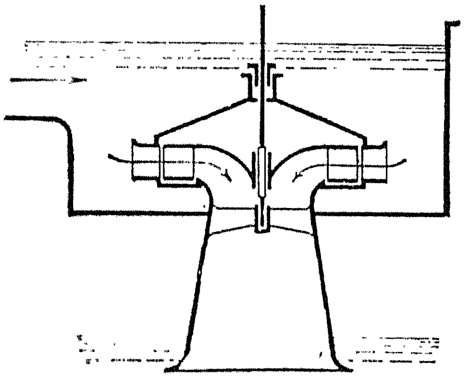

FIG. 1 ORIGINAL FRANCIS TURBINE

In the States, it was realized quite a number of years ago that high specific speed is one of the most important factors in decreasing the cost of a low-head development and since about 1900 the American-designed high specific speed Francis turbines have been generally used, notwithstanding their lower efficiency.

The evolution of the Francis turbine during the last 50 years is indicated by Figs. 1 to 6 inclusive. Fig. 1 shows the original conservative Francis design. The column of water is divided into separate streams and admitted to the runner by means of regulating vanes or wicket gates. The position of the vanes, determined by the governor, depends on the operating conditions and varies from practically closed position at no load to full open position at maximum load. The vanes are shaped and arranged so that at each position of the gates a certain amount of water is admitted, without throttling action and without power losses due to such action. The water streams formed between two adjacent vanes enter the runner at a certain angle, which depends on the position of the gates. In order to insure maximum efficiency, the flow through the turbine should be smooth and without rapid change either in the direction or in the velocity of the individual streams. This is accomplished by the proper combination of the velocity and direction of the streams, flowing from the wicket gates, with the shape of the runner vanes or buckets and the proper number of revolutions of the runner. For each position of the wicket gates a certain shape of the runner buckets and a certain number of revolutions of the runner will give maximum efficiency. Since it is obviously impossible to change the shape of the buckets there is a certain opening of the wicket gates and a certain number of revolutions of the runner that corresponds to the maximum efficiency at a given head. At every other opening of the gates, the efficiency will be lower even if the number of revolutions of the runner could be properly adjusted. In the practical operation, the number of revolutions is held constant; consequently at every opening of the gates, other than the most favorable one, the efficiency will be lowered. The same conditions apply if there is a change in the head for which the turbine is designed. In other words, for each turbine at a given head and given number of revolutions, there is a certain opening of the gates or a certain loading at which the turbine develops its maximum efficiency; under any different head or loading the efficiency will be lower.

In the conservative Francis design shown by Fig. 1, the water, after passing the gates, enters the buckets and the conversion of energy takes part during the time the water flows in horizontal streams through the buckets. After the water leaves the buckets the water streams are deflected and their direction is changed by the deflector. In such a turbine the action of the water is distinctly subdivided as follows:

1. The water is divided into separate streams by the gates and flows at a certain angle toward the runner buckets.
2. The conversion of energy occurs in the buckets.
3. The direction of the water streams is changed and they unite in a single water column entering the draft tube.

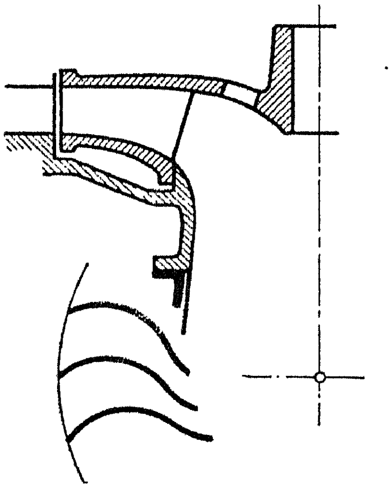

FIG. 2—FRANCIS TURBINE FOR HIGH HEADS

Reduced specific speed

The specific speed of such a turbine may be changed within rather narrow limits by changing the shape of the buckets. If the specific speed is to be changed more radically, then a modification of this design is necessary. If the head is high and it is desired to reduce the specific speed, then the modifications shown by Fig. 2 are made. The change consists principally in increasing the outside diameter of the runner and thus have a smaller number of revolutions, but with the same peripheral speed and hence a lower specific speed. The height of such a runner must be reduced so as to pass the same amount of water and thus have the same discharge. If at the same time the shape of the buckets and particularly the entrance angle is changed, as indicated by the drawing, then a further reduction of specific speed may be made by reducing the velocity of the water entering and leaving the runner. The result will be a turbine with a smaller number of revolutions and lower specific speed than the original Francis design, but of larger physical dimensions.

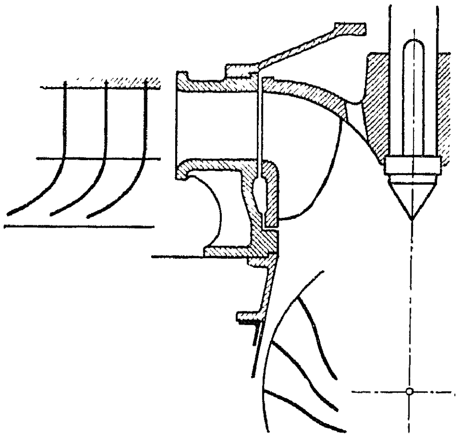

Fig. 3—Francis Turbine for Moderately Low Heads

Higher specific speed

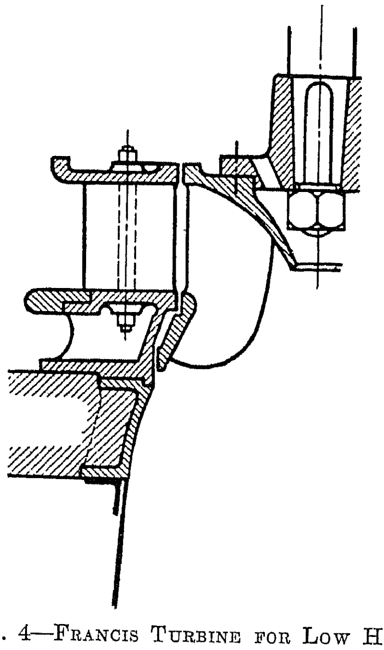

Fig. 4—Francis Turbine for Low Heads

High specific speed

If the head is low and it is desired to increase the specific speed, then the modification indicated by Fig. 3 may be made. The diameter of the runner is decreased and the height of the wicket gates is increased; this increases the specific speed by increasing the number of revolutions so as to retain the same peripheral speed. The change of the shape of the buckets makes possible a still larger increase in specific speed owing to the increase of the water velocity. In such a design the water velocities will be higher and the runner more cramped than the original Francis runner. After the water streams leave the gates the conversion of energy from the water to the runner and the deflection of the direction of the water flow in the individual water streams occur simultaneously, contrary to the original Francis design.

If a still higher specific speed is desired, then the conditions indicated by Fig. 4 are encountered. The runner is so cramped that in order to have satisfactory conditions and a reasonably low water velocity at the draft tube inlet, the diameter of the draft tube entrance must be made larger than the runner diameter. Such a design will result in high specific speed and small size, but a much less satisfactory turbine than the original Francis design. The high water velocities cause high friction losses and even under most favorable loading conditions the efficiency will be comparatively low. For other loadings or for varying heads the cramped conditions and the high water velocities are responsible for the very high eddy losses, which rapidly reduce the efficiency. To reduce the friction losses in such high specific speed turbines, the modification of design indicated by Fig. 5 may be adopted. Here the friction areas are reduced by leaving a free space between the wicket gates and buckets.

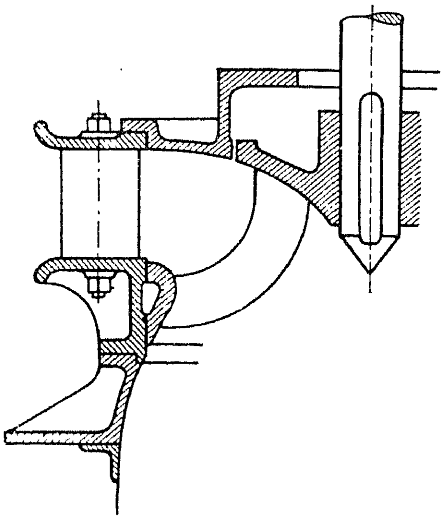

Fig. 5—High Specific Speed Francis Turbine with Reduced Area of Buckets

The final step that can be made in this direction is indicated by Fig. 6, where the runner has no buckets but properly shaped radial partitions.

The design tendency that was developed in an attempt to increase the specific speed and to make Francis turbines better suited to low-head developments was checked and any further increase in specific speed was stopped by: (1) the decrease in efficiency on account of increase in specific speed; (2) the sensitiveness of such turbines to variations in head; or in other words, a rapid decrease in efficiency when operating under heads different from that for which the turbine is designed; and (3) cavitation and resulting destruction of the runner.

The introduction by Kaplan of the propeller turbine changed the situation radically and made it possible to build turbines of much higher specific speeds, which showed high efficiency at the most favorable loading and were much less sensitive to variation in head. Finally, the introduction by Kaplan of propeller turbines with adjustable blades—known as Kaplan turbines—extended the high efficiency of propeller turbines over a wide range. The danger of cavitation limits the present use of propeller and Kaplan turbines to a head which at present is about 100 feet.

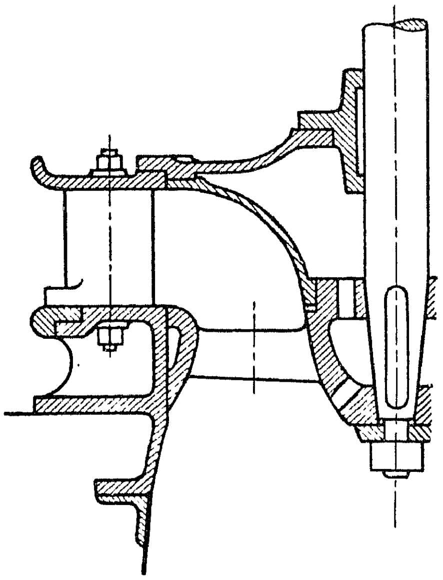

Fig. 6—High Specific Speed Francis Turbine with Radial Partitions

The propeller or Kaplan turbine is somewhat similar to the high-speed Francis turbine shown by Fig. 6, with this important difference, however, that all friction surfaces are reduced as far as possible by substituting for the Francis runner the propeller runner with its small area.

The difference between the Francis, propeller, and Kaplan types of turbines is well illustrated by Fig. 7, which shows the very satisfactory efficiency curve obtainable from a very low-specific speed Francis turbine and the less satisfactory curve for Francis turbines of high specific speed; in this respect, the propeller turbine of still higher specific speed is very much in line with the Francis turbine. Taking finally a properly designed high specific speed propeller turbine and changing it to a Kaplan turbine, with adjustable blades, not only gives a better range of efficiency than the lowest specific speed Francis turbine shown on the diagram, but at the same time results in a turbine that can stand considerable overloading and yet retain satisfactory efficiency.

## CAVITATION

All theoretical considerations of the action of water, not only in a turbine but also in any part of the hydro development, are based on the assumption that water is not compressible and consequently does not change its specific weight under different pressure conditions. So far as increase of pressure above atmospheric is concerned, the compressibility of the water is so small that the assumption of incompressibility holds for all practical purposes. With the decrease of pressure below the atmospheric this assumption holds until the pressure is decreased to the evaporation pressure corresponding to the temperature of the water. If the pressure is lowered below that point, then a sudden change in conditions occurs; "cold boiling" of the water takes place and the resulting mixture of water and steam becomes highly compressible. Under these conditions all of the assumptions on which the theoretical design is based become suddenly invalid. A very interesting confirmation of this theory was obtained in some laboratories in Europe, by running comparative turbine model tests on cold and heated water.

The cavitation phenomena are treated in more detail in the paper by L. M. Davis and G. W. Spaulding.* Here it is sufficient to state that the pressure drop depends on the water velocity and acceleration.

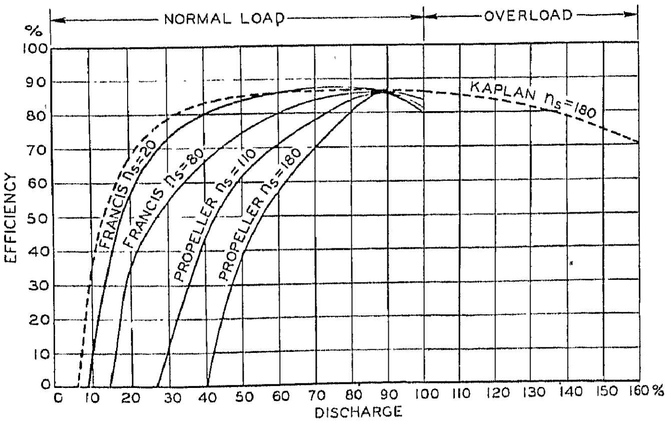

Fig. 7—Comparative Efficiency Curves of Francis, Propeller, and Kaplan Turbines

The pressure and velocity conditions in a water stream passing an immersed body are illustrated by Fig. 8. The velocity reduces practically to zero at the point, *a*, of the immersed body where the maximum pressure occurs. The pressure and velocity changes are clearly shown on the diagram.

Fig. 9 shows the pressure conditions in a water column passing through a pipe with smoothly decreasing and increasing cross-sections. The velocity is highest at the smallest section, where the pressure is lowest, due to the pressure drop caused by accelerated velocity. After passing the smallest section, the water column is retarded, the velocity decreases and the pressure increases as indicated in the diagram by solid lines. If the friction losses are taken into account, the pressure curve will change as indicated by dotted lines.

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*See page 220.

These simple cases show that even in the non-turbulent uniform or non-uniform flow, depending on the velocity and acceleration conditions, any pressure less than the original may be created, even down to the evaporation pressure or lower. Also, depending on the acceleration and retardation of the velocity of the water stream, the pressure may drop below the evaporation pressure at some point in the stream and increase again above that pressure in some succeeding section.

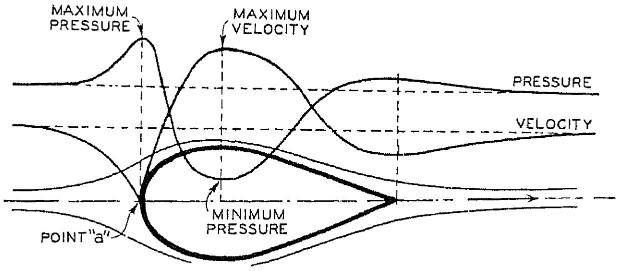

Fig. 8—Velocity and Pressure Diagrams of a Water Stream Passing an Immersed Body

If the water flow is turbulent, then the elementary water streams are to be traced in the eddies, and the pressure changes will be much more rapid due to the longer paths that the elementary water streams travel and the unsteady acceleration and velocity conditions.

## The Behavior of the Water Stream at Low Pressure Zones

All water contains a certain amount of air corresponding to its pressure. When the pressure decreases the air occluded in the water is released and forms bubbles. This is a gradual process, the size and number of the bubbles increasing with decrease of pressure, but certain bubbles can be formed even before the pressure is reduced to the evaporation pressure. When the pressure drops below the evaporation point, the number and size of the bubbles increases very rapidly; these bubbles contain a mixture of air and vapor. So long as the flow is non-turbulent, the lowest pressure—and consequently the formation of bubbles—takes place somewhere along the boundaries of the stream but not inside the water column. In case of turbulent flow the lowest pressure and the formation of bubbles will occur along the center line of the eddy. A certain time element is necessary for the formation of bubbles, and particularly air bubbles, at pressures higher than the evaporation pressure. Water passing very rapidly through a low pressure zone may not release bubbles while water, under the same pressure conditions, but passing more slowly through the low pressure zone, may release a considerable amount of bubbles.

The velocity and acceleration of that part of the water stream which adjoins the boundaries depend to a large extent on the surface conditions of these boundaries; a rough surface may augment the formation of bubbles.

## The Phenomena Accompanying Cavitation

The formation of air bubbles, or air-vapor bubbles, of appreciable size, interrupts the continuity of the water column, or water streams, radically changes their condition, introducing irregularities which preclude theoretical analysis. Nearly all hydraulic machinery functions in accordance with its design provided the continuity and regularity of the water flow are preserved, but if they are destroyed, then the most noticeable result will be the rapid increase in the amount of energy dissipated in the flow coupled with a rapid decrease in efficiency. That, *per se*, would be a perfectly valid reason to avoid cavitation in turbines. But in addition to a decrease in efficiency, cavitation may also result in the destruction by pitting of the affected parts of the turbine. In spite of much research, the way in which pitting actually occurs is not too clear. It seems to be proven that the cavitation bubbles do not have any destructive effect at the place of formation and that destruction by pitting occurs at places where, due to changed velocity conditions, the pressure again rises above the evaporation point with a consequent disappearance of cavitation bubbles.

A number of attempts was made to determine, by mathematical methods, the conditions under which cavitation bubbles disappear. Such determination cannot be considered very exact because it must be based on a number of rather arbitrary assumptions. Those methods, however, confirm the general theory that if a cavitation bubble is contained in a water column or water stream which is under increasing pressure conditions, a rapid squeezing of such bubble occurs. This squeezing results in a rapid increase in temperature within the bubble and when this occurs in contact with a hard substance, it will be accompanied by a localized increase in unit pressure, the intensity of which increases very rapidly with a decrease in the size of the bubble.

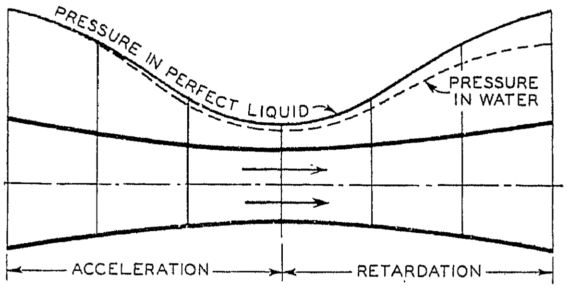

Fig. 9—Pressure Diagrams of an Accelerated and Retarded Water Column

The mechanics of the pitting can be considered as follows:

Bubbles in contact with the surface of some part of the turbine are rapidly diminishing in size and finally collapse with the result that the adjacent metal is bombarded by the residual, very minute particles of air, under tremendous pressure and at high temperatures. At the same time it is probable that such temperature enables the oxygen in the bubble to form a direct chemical reaction with the affected part and this will increase the pitting still further.

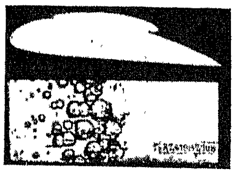

Fig. 10—Glass Model of a Runner Blade Subjected to Cavitation

Cavitation tests which showed that chemically inert glass is much more rapidly destroyed by pitting than any of the commonly used metals seem to support the theory that mechanical action is the most potent factor in pitting. On the other hand, the better cavitation resistance of stainless steel as compared to cast iron or cast steel indicates that the chemical action may be of some importance.

Pitting does not occur in low pressure zones, where the cavitation originates, but rather in rising pressure zones, where the cavitation bubbles are destroyed; this is why the pitted zones are so irregular.

Fig. 10 is an illustration of a glass model of a runner blade which was subjected to cavitation. It shows the formation of cavitation bubbles in the low pressure zone and their disappearance in a zone where the pressure was higher than the evaporation pressure. The bubbles disappeared on that part of the blade where the pitting began. This is the simple case where cavitation bubbles are formed at the surface of the blade in non-turbulent flow and carried by the water flow along the face of the blade into higher pressure zones where the bubbles collapse and in so doing destroy the material of the blade by pitting.

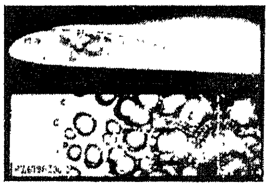

Fig. 11—Glass Model of a Runner Blade with Extended Cavitation Area

The same model blade is shown again in Fig. 11 but under different conditions, which were arranged so that the low pressure area extended along the blade; in this case the bubbles were carried away by the water flow and no pitting occurred on the blade itself. The same thing may occur when cavitation bubbles are formed in a turbulent flow along the center line of an eddy. Such bubbles may be carried irregularly a considerable distance. If they finally reach a high pressure zone without contacting any part of the turbine, they will disappear and merely cause unsteady flow conditions, coupled with the characteristic noise that accompanies cavitation. However, if, in approaching a higher pressure zone, cavitation bubbles come into direct contact with any part of the turbine, they will bombard and pit that particular part.

Fig. 12 shows a cross-section through a cast iron part subjected to cavitation. The spongy appearance was caused by gradual destruction, starting with the particles that offered least resistance. In the case of cast iron, the large graphite particles are easily disintegrated and washed away first and the iron particles are removed afterwards. This picture shows clearly how non-uniformity in the material or rough spots may help to start pitting and accelerate the destruction of the material.

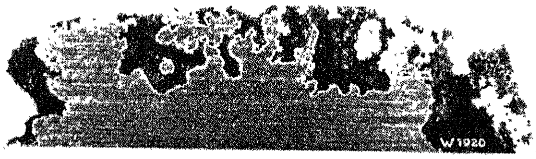

Fig. 12—Cross-Section Through a Cast Iron Part Subjected to Cavitation

## Design Theories

From the instant the water enters the stationary guide vanes in the conservative Francis turbine until it leaves the runner, it is confined between two relatively close adjacent partitions. The parts which guide the water are practically continuous; their curvature changes so gradually that the water does not break contact with them and at the same time it passes through the turbine at moderate velocities so that the friction losses are low and no harmful eddies occur. The customary design method is to assume a very large number of vanes; hence the entering water is divided into an equal number of filaments, in each of which the conditions with respect to every cross-section are constant, and it is sufficient to analyze only the velocities and pressures along the center line of each filament. Under such conditions satisfactory results may be obtained by applying the most simplified one dimensional hydraulic theory, under assumption of a stream line, non-turbulent flow and a perfect liquid the viscosity of which is zero.

In changing to higher specific speed Francis turbines, with rapidly increasing friction and eddy losses, the same design method does not give very satisfactory results and must be checked by model tests to ascertain in each case how close the design satisfies the actual conditions.

In propeller and Kaplan turbines, the water is not guided as it is in the Francis type and none of the assumptions on which the designs of Francis turbines were based are valid. The problem now becomes two or three dimensional, with the velocity and pressure conditions of the water changing not only in the direction of the main flow but at every section taken at right angles to that flow. The hydraulic theories fail entirely and the design becomes a problem in hydrodynamics.

At present complete solution of the general hydrodynamic equations of a physical liquid, the viscosity of which is not zero, is not known. If an attempt is made to handle the hydrodynamic problem, by incorporating the simplifying assumption of a perfect fluid, the viscosity of which is zero, then the theoretical results are so opposed to actual conditions that they cannot be used. Probably the most striking deficiency of the theory is that in such liquid neither can eddies be formed nor can the laminated steady flow be changed to turbulent flow. That makes it necessary to approach the subject in a less formal way by introducing approximate theories which, within certain limitations, give results that for practical purposes are near enough to the actual conditions.

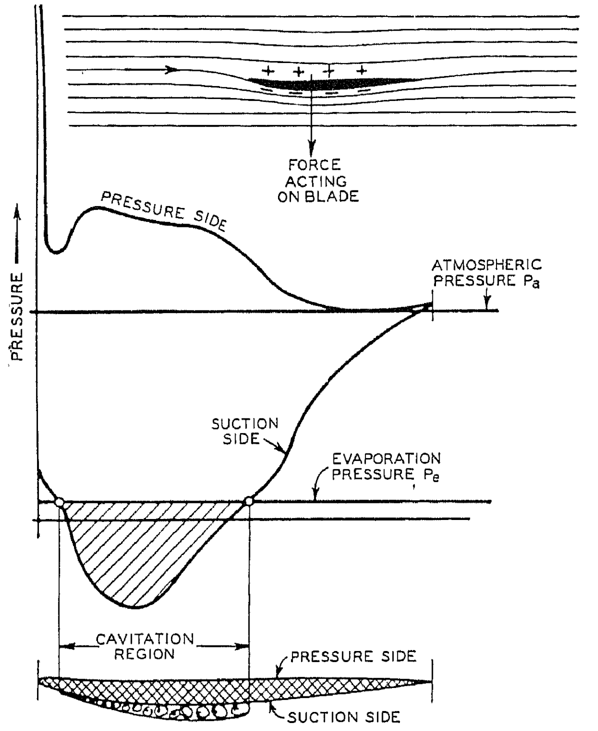

Fig. 13—Pressure Conditions Along the Surfaces of a Single Propeller Runner Blade

Probably the most important of such theories is the boundary layer theory of Prandtl, which is based on the idea that the water column behaves as though water were a perfect liquid. This is due to the very low viscosity of water and no appreciable error is involved if the viscosity is neglected entirely. The important difference occurs only along the boundaries, where the film of water which covers them has the same velocity as the boundaries. Here the difference in the velocities of the adjoining water films may be so large that even the very low viscosity of water will have a considerable influence and cannot be neglected. A rapidly moving water column among immovable boundaries may be considered as such an instance. Consequently, the theory of Prandtl assumes that in its flow the water behaves as a perfect liquid except for a comparatively thin layer that adjoins all boundaries. In this layer the velocity of the water changes from the velocity at the boundaries to the velocity of the main stream.

This theory also gives a satisfactory explanation of the formation of eddies. In the case of retarded velocities the pressure in the boundary layer may become lower than the pressure in the adjoining water stream; then the boundary layer is curled into the higher pressure zones of the main stream, turning in the upstream direction, breaking away from the boundaries and starting an eddy. Such phenomena do not occur under accelerated velocity conditions of the water stream. The results of this theory agree very closely with the actual conditions.

The next in importance is the Kutta-Joukovsky theory concerning the forces acting on a body immersed in the flowing stream of a liquid and the application of this theory to the design of propeller blades. This theory is very simple as long as a single infinitely long blade is considered, but gets complicated when the actual condition of a number of short blades is considered.

All these theories give a possibility to handle the problems mathematically or graphically and are very satisfactory is applied to a steady, laminated flow. They fail entirely if an attempt is made to apply them to a turbulent flow.

## Design of Propeller and Kaplan Turbines

The action of the water column that passes through a propeller or Kaplan turbine can be subdivided into four major parts:

1. The action of the water entering the unit, including the intake, scroll case, guide and regulating vanes or wicket gates, where the water column is divided in a number of streams.

2. The action of the water after it passes the guide vanes and before it strikes the runner blades. Here, due to the way in which the water is guided by the guide and regulating vanes, the water streams are united in a revolving water column that has two distinct velocity components, one parallel to the axis of the turbine and the other rotating around this axis.

3. The action of the water when it strikes the runner blades and the revolving water column is again divided in a number of streams.

4. The action of the water after it leaves the runner and the water streams are united in a column that flows through the draft tube until it reaches the tailrace.

*Water Entering the Unit.* The first part is very much the same in a propeller or Kaplan turbine as in a Francis turbine and may be handled in the same way.

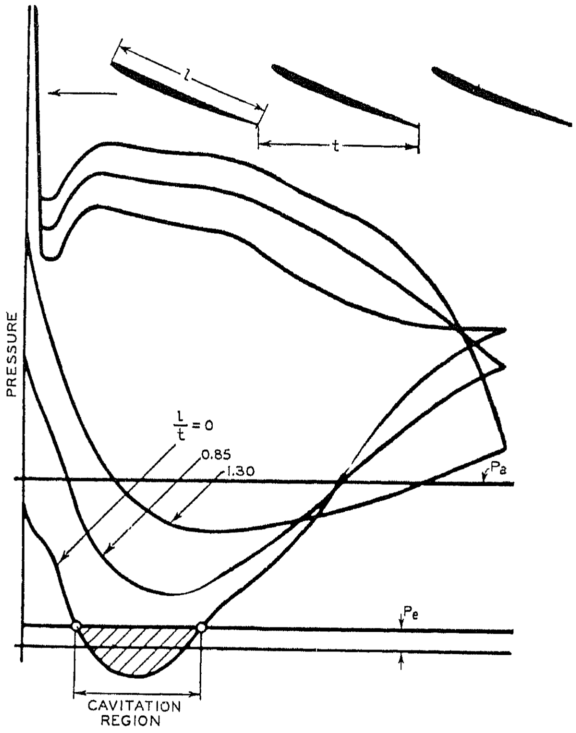

FIG. 14—PRESSURE CONDITIONS ALONG THE SURFACES OF A NUMBER OF PROPELLER RUNNER BLADES

*Revolving Water Column.* The second part, the revolving water column, has no analogy with any part of a conservative Francis turbine. The design problem is to arrange all conditions so that the water comes down with minimum friction and eddy losses, and the rotating water column is long enough so that at its end when the water strikes the runner blades, all nonuniformities are smoothed out and there is no difference between the water streams that strike the different blades.

*Water Passing the Runner.* The third part, the water streams passing between the runner blades, again has no analogy in a Francis turbine. The ideal condition will be obtained if the turbine could be so designed that if the runner were removed the flow of the water column in the direction parallel to its axis would be the same as with the runner in place and would not be disturbed by again installing the runner. In that case the conversion of energy from the revolving water column to the runner blades would be accomplished without any disturbance simply by stopping the rotation of the column, so that after passing the runner the water column would enter the draft tube and flow through it with only a velocity component parallel to its axis and with no circumferential velocity components. Such conditions can hardly be obtained in the practical design and in most cases only a partial retardation of the rotation of the water column can be accomplished.

Fig. 13 shows the pressure conditions of a water stream passing a single blade. Fig. 14 shows to what extent in similar runner designs a change of the number of blades will influence the pressure conditions. The upper part of this diagram shows a developed circumferential section taken parallel to the axis of the runner. Since $l$ is the width of the blade and $t$ the spacing, the ratio $\frac{l}{t} = 0$ denotes the conditions of a single runner blade. The other values of $\frac{l}{t}$ show different numbers of blades. The pressure, $P_a$, is the atmospheric pressure. The pressure, $P_e$, is the evaporation pressure of the water. The shaded area below $P_e$ shows the cavitation region at the suction side of the blade.

This diagram shows that the value of $t$ has to be reduced or the number of runner blades increased to diminish or remove the cavitation danger.

Fig. 15 shows the average pressure of the water passing through the turbine; the lowest average pressure occurs at the draft tube inlet. But in the individual water streams that pass between the runner blades the pressure may be considerably lower than shown in this diagram.

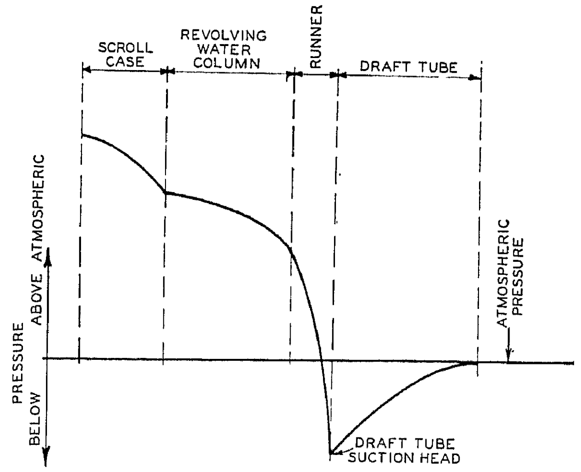

FIG. 15—AVERAGE PRESSURE CONDITIONS OF A WATER COLUMN PASSING THROUGH A TURBINE

The superimposing of the diagrams of Figs. 14 and 15 will show that the part of the water stream which passes along the pressure side of the blade will have a pressure higher than the pressure at the draft tube inlet. On the contrary, that part of the water stream which passes the suction side of the blade will show lower pressure than the pressure at the draft tube inlet. These pressure differences are essential in the turbine, since they are converted into forces that rotate the runner, converting the energy of the water into mechanical energy that is transmitted through the shaft to the generator.

In order to increase the forces acting on the blades, it is necessary to increase the pressure difference between the two sides of the blade, which in turn will retard more effectively the rotation of the water column.

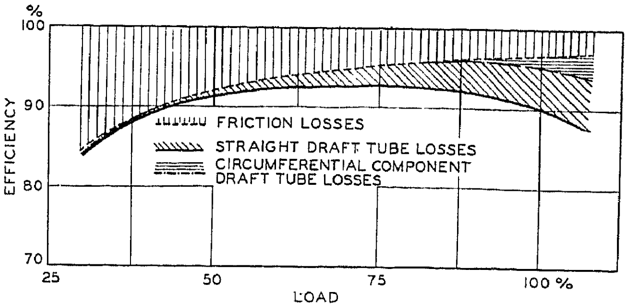

Fig. 16—Losses of a Kaplan Turbine

The amount of pressure drop on the suction side of the blades depends upon the shape and number of the blades, and the force that is to be transmitted from the water streams into each individual blade. In order to reduce the cavitation danger the force per unit of blade surface that is transmitted from the water streams into the runner should be as small as possible. This means that the total area of the runner blades should be as large as possible and the retardation of the rotation of the water column as small as possible. On the other hand, in a propeller or Kaplan turbine, the water strikes the blades at high velocity and an increase in the number and area of the blades rapidly increases the friction losses and lowers the efficiency. In addition, the number of blades in a Kaplan runner should be kept low to satisfy mechanical considerations.

The foregoing indicates the problem that must be solved in designing a highly efficient propeller or Kaplan turbine. The shape of the blades should be such as to correspond to the most favorable conditions in so far as cavitation is concerned; the number and total area of the blades should be as small as possible but at the same time large enough to avoid cavitation danger and to utilize the whole water column, thus not giving the water a chance to escape between the blades without performing useful work.

*Water Passing the Draft Tube.* The fourth part—the action of the water in the draft tube—is very similar to the Francis turbine. The principal difference is that the higher velocity under which the water enters the tube makes it necessary to regain a much higher percentage of energy in the draft tube. This means that the draft tube efficiency has a larger influence on the total efficiency of the unit. At the same time the size of the draft tube and the large amount of water make such turbines very sensitive to irregular conditions and disturbances in the draft tube. Probably the most sensitive section is where the water leaves the runner and enters the draft tube. Here the water does not represent a uniform, solid column, but close to the axis of the turbine there is formed a low pressure area which is filled mostly with air and which extends into the tube. If, due to deficiencies of design, the air is not carried away by the water, an air bubble of considerable size may be formed. If the pressure at this point is lower than the evaporation pressure of the water, then a cavitation air-vapor bubble of still larger size may be formed, which may collapse and may rebuild itself at irregular intervals, thereby causing unsteady conditions in the draft tube, resulting in load swings. Such swings are becoming more and more prevalent in recent plants, due to increase of the draft tube diameter and the water velocity.

In the larger sized Francis turbines of the past, an effective remedy against such load swings was to vent outside air into the draft tube. If a sufficient amount of air was admitted, then the pressure was raised, the formation of bubbles was prevented and the turbine was steadied. However, the admission of air lowers the suction head and may lower considerably the efficiency of the draft tube. For high head developments, where the amount of energy regained in the draft tube is only a small part of the total energy, the lowering of the efficiency of the draft tube has small influence on the total efficiency of the unit. For low-head developments such lowering may considerably influence the total efficiency of the unit. Here, as in many other cases, a turbine of high efficiency is much more sensitive to outside disturbances than a low efficiency turbine. High efficiency requires not only a unit better designed but also better protected against all disturbing influences. Since it is not reasonable to build and pay for a high efficiency turbine and afterward lower its efficiency by admitting air in order to have it run steady, considerable effort was spent in

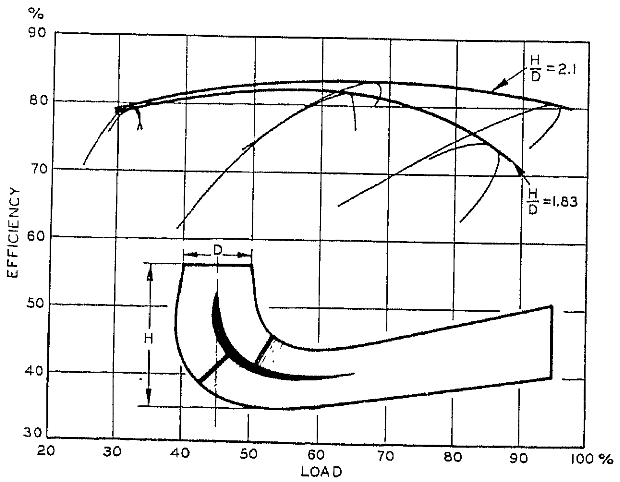

Fig. 17—Comparative Efficiency Curves of Draft Tubes of Different Height

investigating the conditions and finding ways to build highly efficient, steady units. The first step was made by Professor Kaplan, who increased considerably the size of the end piece of the runner forming the familiar heavy hub of the propeller and Kaplan turbines; this decreased considerably, and at the most vulnerable point, the size of the bubble that could form.

The next step, taken in Europe, was based on the idea that with a constant increase of the size of the draft tube the conditions are rapidly approached that make it impossible to handle satisfactorily such large columns of water. By dividing the large water column into smaller ones, much more satisfactory conditions were obtained. In the beginning this idea was prompted by structural considerations where in the larger units the size of the outlet of the tube increased to such extent that structural difficulties were encountered. The result was the introduction of vertical partitions in the draft tube outlets. These partitions were very helpful structurally and being built in the horizontal part of the tube, far from the runner, they exerted only a slight influence on the hydraulic conditions. Next, baffles were tried at right angles to the vertical partitions, but starting close to the runner. The first tests of such baffles showed that although they considerably steadied the unit, they lowered the efficiency.

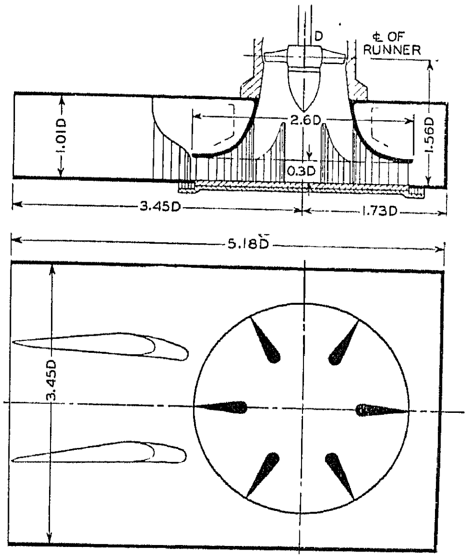

Fig. 18—Shallow Draft Tube of Spaunhake

Further investigation disclosed that the reduction in efficiency is due principally to the circumferential component of the velocity of the water column as it leaves the runner. If this component was considerable, then the baffle broke it up and prevented the regaining of the energy in that component or, in other words, the baffles were very beneficial for axial flow and detrimental for rotating flow.

It was found that a satisfactory compromise can be made by moving the baffles away from the runner to a point where their unfavorable influence on the efficiency was small but still in a region where the division of the water column was effective in steadying the draft tube conditions and the loading characteristics of the unit. Such baffles are used in most of the larger sized units designed in Germany and Switzerland.

Fig. 16 gives an idea of the distribution of losses in a Kaplan turbine. First and most important are the runner friction losses, which are mainly responsible for the low efficiency at smaller loadings. Second, the straight draft tube losses, which are very small at partial loadings but increase with the increase of load. Third, the draft tube losses due to the circumferential velocity component which in this particular turbine appear only at high loadings.

The major part of the losses at high loadings are draft tube losses and great effort was made to diminish them. Fig. 17 shows the results of investigations on Kaplan turbines with elbow type draft tubes, and shows the favorable influence of the increased height of the tube, but this is very expensive, since it necessitates deep excavation and extra concrete. Therefore, research was made to find the most favorable type of shallow draft tube.

The very shallow design shown by Fig. 18 was developed after considerable research work on draft tube models by Professor Spannhake in Karlsruhe. The idea of dividing the water column after it leaves the runner is treated in an original and interesting way. By means of partitions the vertical part of the water column is divided into six and the horizontal part into three streams. At the same time the central part of the vertical water column is not interfered with. This design suggests that further improvement is possible in developing designs which will enable the energy to regain to a larger extent the circumferential component of the water velocity.

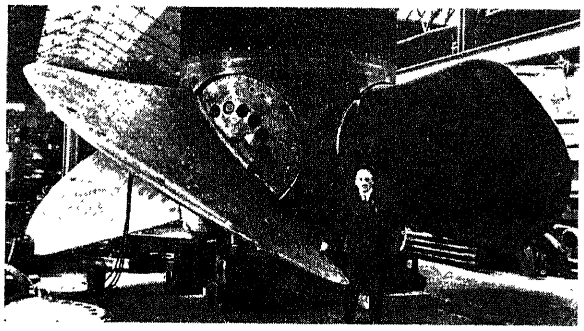

Fig. 19—Stainless Steel Runner of the Swir Unit (No. 10)

## Research

Recent low-head developments in the United States show conclusively the insufficient amount of theoretical and model research work that has been done in connection with the development of hydraulic machinery.

The contention, so common in the past, that laboratory research can be substituted by observation or study of units in actual operation is very misleading. The operation of the finished unit is the supreme test of all theoretical and laboratory work on which the design was based. But the many factors involved, which cannot be separated in the operating plant, presents a problem so complicated that probably only in exceptional cases can valid conclusions be reached by a study of operating conditions. The proper study necessitates the separation of the different problems and their independent solution. In most cases this can be done economically only in the laboratory.

Instead of limiting the laboratory work to the customary efficiency determinations, a number of new and important laboratory investigations is necessary. The most spectacular are the cavitation problems. The theoretical considerations concerning cavitation can be determined only in the laboratory.

The first fundamental question is, under what operation conditions will cavitation begin in a certain unit? Next, what can be done so far as the design of the runner and all other parts of the turbine are concerned to eliminate cavitation and to permit either a higher specified speed or a higher setting? Finally, can the turbine be run under the conditions at which cavitation will start but be so slight as to be tolerated?

So far as efficiency is concerned, a reasonably smooth cast runner without machining or surfacing will probably show the same efficiency as a similar runner machined and highly polished. So far as cavitation is concerned, a remarkable and surprising difference may be obtained by the substitution in the prototype of machined and polished surfaces for the rough surfaces of castings. The European practise follows the only logical way, which is first to determine by model experiments in the laboratory the best shape of the runner blades and then to build an exact prototype, machined and polished on all surfaces which come in contact with flowing water.

One of the important researches in connection with cavitation is that pursued in Sweden and Germany in establishing the relative corrosion resistance of different materials. Obviously, it is necessary to know which of the available materials best resists corrosion. Sample plates of different materials were kept in flowing water under conditions of cavitation. The series of materials so far investigated begins with glass, which was found to have the least resistance, and ends with stainless chromium steel which has the greatest resistance.

A considerable amount of theoretical data necessary to design runner blades is based on the laboratory work made in aero-dynamic laboratories in connection with airplane propellers. Theoretically and practically, there is a similarity between the conditions of a uniform flow of water impinging against the blades of a propeller or Kaplan turbine, and a uniform flow of air against the blades of an air propeller. Since tests on air models are much simpler and much more feasible than on water models, it is clear why so many important contributions to the theoretical design of propeller and Kaplan turbines came from aero-dynamic laboratories. Many of the present investigations in hydraulic laboratories consist of picking up threads left by the aero-dynamic investigations.

Finally, for Kaplan turbines, there is a peculiar field of tedious laboratory work that is necessary on account of the imperfections of the present day governor design. The governor of customary design regulates the wicket gates so as to provide the amount of water that corresponds to the loading. The position of the runner blades is set mechanically by the governor to a position that was predetermined by laboratory tests. In so far as the efficiency is concerned, the relationship which gives the most favorable combination between the opening of the wicket gates and position of the runner blades changes with varying head and a considerable number of laboratory tests are necessary to cover all operating conditions. Even after that is done, it may be necessary to check this information by actual operation tests.

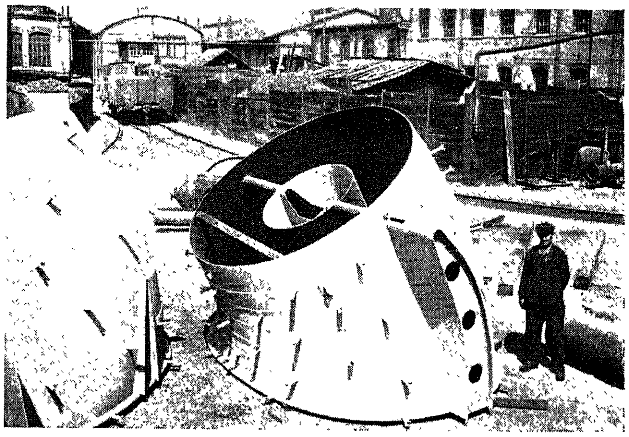

FIG. 20—STEEL LINER OF DRAFT TUBE INLET OF THE WETTINGEN UNIT (NO. 2)

Notice the baffle liner and the stationary extension of the runner hub

## LARGE SIZED KAPLAN TURBINES

The data available pertaining to the more important recent developments are collected in Table I. At present there are two different designs of the larger sized Kaplan turbines, the German-Swiss design, which is followed very closely by the latest American designs, and the Swedish designs. The main difference is in the location of the servo-motor for operating the runner blades. In the German-Swiss designs, the servo-motor

TABLE I—LARGE SIZED KAPLAN TURBINES

| Number | Development | Country | Manufacturer (1) | Head in ft. | Output in hp. | Revolutions per minute | Discharge in c.f.s. | Diameter of runner in ft. | Specific speed | No. of runner blades | Draft tube baffle (2) | Material of runner blades (3) | Surface of runner blades (4) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Shannon | Ireland | V | 106.5 | 33,000 | | | 13.15 | | 7 | | St. | m |
| 2 | Wettingen | Switzerland | E | 76.3 | 10,700 | 214.0 | 1,425 | | 98 | 6 | B | | m |
| 3 | Gronvollfoss | Norway | V | 75.5 | 18,400 | | 2,650 | | | 6 | | C | m |
| 4 | Sages | Russia | K | 65.7 | 17,000 | 167.0 | | | 119 | | | St | |
| 5 | Mixnitz | Austria | V | 64.4 | 12,150 | 215.0 | 1,940 | 10.05 | 143 | 6 | | C | m |
| 6 | Safe Harbor | U. S. A | S, M | 55.0 | 42,500 | 109.1 | 8,000 | 18.33 | 151 | 5 | no | C | |
| 7 | Munkfors | Sweden | K | 50.5 | 15,000 | 167.0 | | 12.15 | 151 | | | St | |
| 8 | Eching | Germany | E | 39.4 | 12,000 | 167.0 | 3 155 | 13.12 | 168 | | B | C | m |
| 9 | Ryburg | Germany-Switzerland | V, E, C | 37.7 | 38,700 | 75.0 | 10,420 | 22.97 | 157 | 5 | B | C | m |
| 10 | Swir | Russia | K | 36.1 | 37,500 | 75.0 | 10,240 | 24.35 | 164 | 5 | | St | |
| 11 | Abborfors | Finland | K | 35.8 | 16,000 | 107.0 | 4,520 | 14.96 | 155 | | | St | |
| 12 | Dogern | Germany-Switzerland | E | 35.1 | 35,500 | 75.0 | 10,600 | 22.97 | 166 | 5 | B | C | m |
| 13 | Lauforsen | Sweden | K | 30.3 | 13,000 | 94.0 | 4,310 | 15.65 | 151 | | | St | |
| 14 | Laholm | Sweden | K | 27.9 | 16,000 | 83.3 | 5,860 | 18.05 | 164 | | | St | |
| 15 | Klingnay | Switzerland | V | 26.9 | 20,000 | | 7,070 | | | | | C | m |
| 16 | Klingnay | Switzerland | E | 23.5 | 18,400 | | 8,160 | 21.20 | | | | C | m |
| 17 | Lilla Edet | Sweden | K | 21.3 | 11,200 | 62.50 | 5,155 | 19.03 | 144 | 4 | no | | |
| 18 | Vargon | Sweden | K | 14.1 | 15,200 | 46.90 | 11,090 | 26.25 | 211 | 4 | no | St | |

(1) For the names of manufacturers the following abbreviations are used:
C—Ateliers des Charmilles—Switzerland.
E—Escher-Wyss—Switzerland.
K—Verkstaden Kristinehamn—Sweden.
M—I. P. Morris Division—Baldwin-Southwork Corporation—United States.
S—S. Morgan Smith Company—United States.
V—J. M. Voith—Germany.

(2) B—indicates a baffle in the draft tube.
no—indicates no baffle in the draft tube.
(3) St—indicates stainless steel.
C—indicates cast steel.
(4) m—indicates that the surfaces of the runner blades are machined.

is located above the runner between the turbine and generator shafts, and the shaft that moves vertically to operate the blades is located in the hollow turbine shaft. The servo-motor is operated by pressure oil which is admitted through the hollow generator shaft. The Ryburg and Safe Harbor units are typical examples.

In the Swedish design of Kaplan runners the servo-motor for operating the runner blades is placed within the runner and the operating pressure oil is admitted through the hollow generator and turbine shaft. Fig. 19 shows such a runner of the Swir development, listed in the table under 10. Note in the table the extended use of stainless steel for the Swedish designed Kaplan runners.

The very scant information available concerning the height at which the center line of the units is set with reference to the normal tail water elevation is given for the developments 5, 6, 9, 17 and 18 in the following table:

TABLE II

| Number | Development | Head in ft. | Center line of runner blades above (+) or below (−) the normal tail water elevation in feet |
|---|---|---|---|
| 5 | Mixnitz | 64.4 | − 1.64 |
| 6 | Safe Harbor | 55.0 | − 6.91 |
| 9 | Ryburg | 37.7 | + 1.30 |
| 17 | Lilla Edet | 21.3 | + 3.20 |
| 18 | Vargon | 14.1 | +14.00 |

## KAPLAN AND PROPELLER TURBINES FOR HIGHER HEADS

There is a considerable tendency to increase the maximum head for which Kaplan and propeller turbines may be used, but two principal handicaps must be overcome:

1. The cavitation danger. In so far as the average runner conditions are concerned, the lowest pressure at the draft tube entrance, shown by Fig. 15, can be kept well above the evaporation pressure. The difficulty lies in avoiding local low pressure areas on the runner blades. Apparently by increasing the diameter of the center piece, or hub, of the runner and reshaping the deflector, or end piece, the conditions can be improved and Kaplan or propeller turbines for still higher heads are feasible. An attempt in this direction is illustrated in Fig. 20, which shows the stationary extension of the runner hub in the draft tube baffle. This design is used in connection with the 10,000 hp., 76 ft. head, Kaplan units of the Wettingen development in Switzerland and is listed in the table under 2.

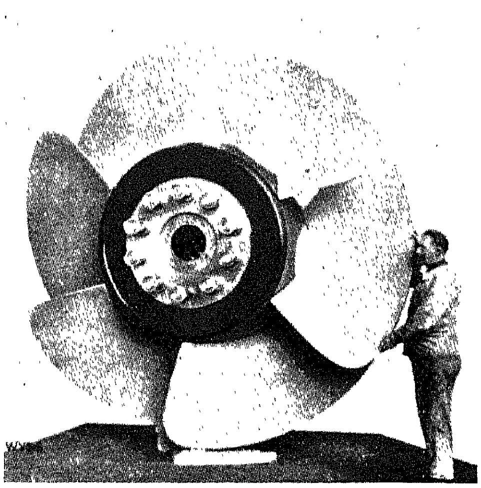

FIG. 21—RUNNER OF THE WETTINGEN UNIT (NO. 2)

2. The rapidly increasing cost of Kaplan turbines for higher heads. This is due to the greater forces acting on the runner blades and as a consequence the necessary increase of the size of the runner hub as compared with the diameter of the runner.

Fig. 21 shows the runner of the same Wettingen development and gives an idea of the size of the hub as compared with the overall size of the runner.

In Table III is given the information pertaining to the comparative size of the hub and runner for the developments 5, 6 and 9:

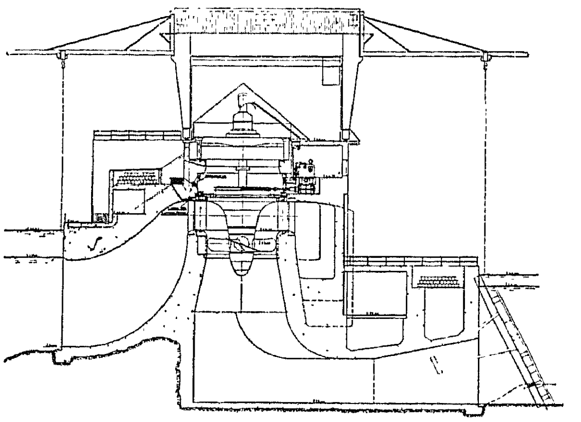

Fig. 22—Cross-Section of the Vargon Unit with Syphon Arrangement (No. 18)

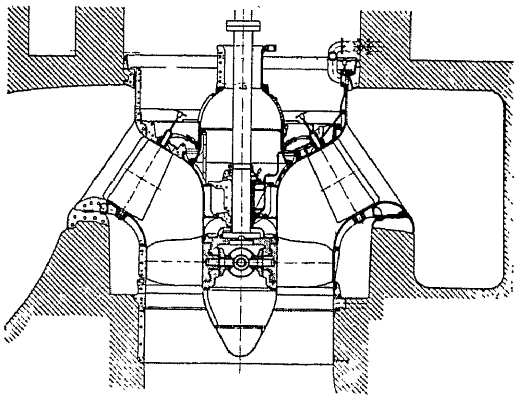

Fig. 23—Cross-Section of a Runner with Inclined Wicket Gates

The Kaplan turbine listed in Table I under 1, the just recently ordered fourth unit of the Shannon development in Ireland, is of particular interest. Not only is the present head of 82.25 feet the highest for which a Kaplan turbine was ever designed, but this turbine is expected to perform satisfactorily even under the future head of 106.5 feet.

TABLE III

| Number | Development | Head in ft. | Diameter of runner in ft. | Diameter of hub in ft. | Ratio of diameters hub/runner |
|---|---|---|---|---|---|
| 5 | Mixnitz | 64.4 | 10.05 | 4.24 | 0.423 |
| 6 | Safe Harbor | 55.0 | 18.33 | 7.20 | 0.393 |
| 9 | Ryburg | 37.7 | 22.97 | 9.85 | 0.428 |

The very radical change that would be involved in materially increasing the head by putting two propeller or Kaplan runners in series has not yet been tried out in practise.

## Kaplan and Propeller Turbines for Very Low Heads

For very low heads the problem is to reduce the cost of handling large amounts of water. The ordinary Kaplan or propeller turbine arrangement requires large amounts of excavation and concrete. The latest trend is to reduce this expense by more suitable arrangements.

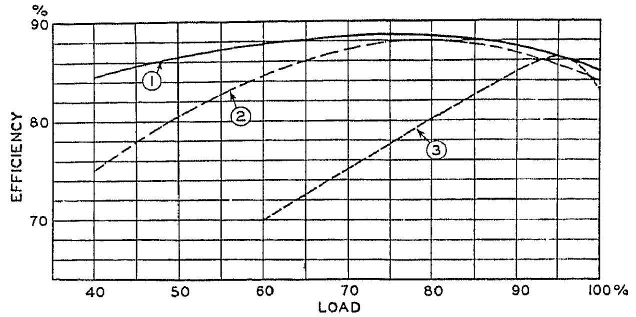

Fig. 24—Comparative Efficiency Curves of a Conventional Kaplan, a Kaplan with Fixed Gates, and a Propeller Turbine

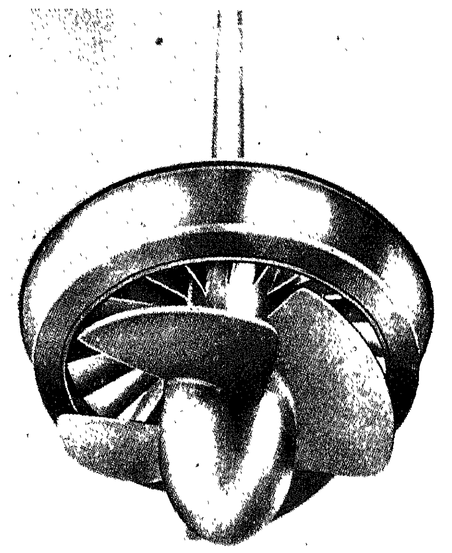

Fig. 25—Kaplan Runner of a Turbine Without Wicket Gates

Fig. 22 shows the largest turbine built, in so far as physical dimensions are concerned. This turbine is located so high that the water entering the turbine must be raised higher than the forebay level. To start the turbine a pump is provided to create a partial vacuum in the space above the runner. After the water starts to flow through the runner, the pump is stopped and the unit operates as an ordinary turbine. To shut down the unit, it is only necessary to admit air which breaks the syphon and stops the water flow. The power house is of the out-door type; the generators are protected by metal covers serviced by a 200-ton gantry crane. This arrangement was adopted in the Vargon development on the Gota River in Sweden and is listed in the table under 18. The simplicity and low cost of this plant and the absence of the expensive head gates opens quite a number of possibilities for similar developments.

An economical arrangement may be obtained by reducing the overall dimensions of the turbine; this can be accomplished by inclining the wicket gates, as illustrated by Fig. 23. This arrangement necessitates a complicated and expensive gate regulating mechanism. A much simpler and less expensive design can be secured by omitting the gates, thus leaving only the guide vanes and regulating the turbine by means of the runner blades only. Fig. 24 shows the efficiency sacrifice by such an arrangement. Curve 1 is for a Kaplan turbine regulated in the customary way, the governor acting on the wicket gates, and the runner blades are set to correspond with the opening of the wicket gates. Curve 3 is for the same turbine when operated as a propeller turbine with fixed blades. Curve 2 is for a Kaplan turbine with locked wicket gates, with the governor controlling only the runner blades. This flat curve shows much more favorable efficiency than a propeller turbine with only a small sacrifice in maximum efficiency which makes the operation of such a unit very satisfactory.

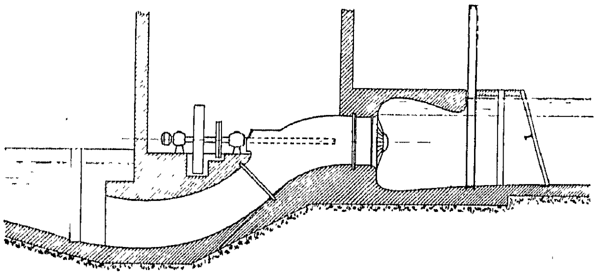

Fig. 26—Cross-Section of a Kaplan Turbine Unit for Very Low Heads

These curves indicate that the customary regulator of a Kaplan turbine, *i. e.*, the governor acting on the wicket gates, may be improved by reversing the conditions and making the governor act on the runner blades and setting the wicket gates mechanically to correspond with the position of the runner blades.

A Kaplan runner with fixed wicket gates is shown by Fig. 25. A very economical design for such a turbine operating under a very low head is shown by Fig. 26. The horizontal shaft of the unit and its low overall dimensions make it possible to build a power house which requires a minimum amount of excavation and concrete.

The combination of fixed inclined guide vanes with a vertical syphon or horizontal unit probably represents the most economical design possible for developments operating under very low heads. A number of such units located along a river and with automatic or remote control, opens development possibilities which were considered economically impossible only a few years ago.

### Acknowledgments

The presentation of this paper was made possible by the support received by the author from Messrs. E. S. Fickes and James W. Rickey, respectively Vice President and Chief Hydraulic Engineer of the Aluminum Company of America, and J. R. Baker, Chairman of the Institute Committee on Power Generation.

## Discussion

**Harry E. Popp:** Unquestionably the economical development of our low-head powers is becoming increasingly important, and the Kaplan adjustable blade turbine, as developed in Europe, furnishes a valuable means of promoting that development. The writer, however, cannot agree with Mr. Karpov that credit for past accomplishment is due entirely to European engineers.

The so-called Kaplan turbine is in reality the combination of the adjustable blade runner and its control mechanism with the usual form of scroll case, draft tube, and miscellaneous mechanical details independently developed and perfected by American engineers. American hydraulic turbine manufacturers by painstaking effort have kept pace with the requirements of the hydroelectric industry in this country as many of their record-making achievements testify. European and American designers have always pursued distinctly different courses. The former have developed elaborate mathematical theories of hydrodynamics as the basis for their designs; the latter have been content with the simpler theories supplemented, however, by painstaking experimental work. This work began with the improvement of runner design at the Holyoke testing flume; it was extended by the several turbine manufacturers to more elaborate testing of runners and other details in their own laboratories; it grew to include the testing and development of competitive types of draft tubes and scroll cases and more recently the experimental investigation of complete models of proposed hydro stations. American manufacturers have spent generously for hydraulic laboratories and for experimental research on their own account and their facilities have been available at nominal expense to power company engineers who have desired to undertake special development work. Not only has the American method resulted in constant improvement in performance and reliability but it has also permitted the maintenance of an economic balance between the cost and value of such improvements.

It is this balance which will determine the extent to which the adjustable blade Kaplan turbine will find application in our future developments. It must not be supposed that it will find universal use in every one of our low-head projects. Nor is there reason to suppose that the adjustable blade runner would not have been adopted at an earlier date in this country had there been a real economic demand for this type of unit. The writer believes that its adoption at this date, several years after its development in Europe, is merely an indication of the different underlying conditions in the hydroelectric industry here and abroad rather than any reflection on the ability or foresightedness of American designers and manufacturers.

In his chapter on draft tubes Mr. Karpov lays considerable stress on the work done in Europe on the development of "shallow" tubes, on the use of baffles and on the regain of the circumferential component of draft tube velocity. All of these have been investigated in America and the results have had wide publicity. N.E.L.A. publication No. 047 of May, 1930, contains the reports of tests of model draft tubes of various shapes and proportions, both of the elbow and concentric types, dating back to 1922. It is interesting to note that, in simplicity and limiting dimensions, the draft tubes developed in these and other tests compare very favorably with the most modern foreign designs. American experience has been that baffles and partitions add but very little to the performance of a properly designed draft tube and that for structural reasons their elimination is desirable.

At the moment, attention is being concentrated on the spectacular subject of "cavitation" and credit is due to European engineers for initiating the investigation of this phenomenon. Certainly, any investigation, theoretical or experimental, which has for its object the elimination of large loss of efficiency or of capacity or of disastrous pitting should be encouraged, but it should not be permitted to overshadow the equally valuable work which has been done and which remains to be done in other directions.

There is also the grave danger that overemphasis of some particular phase of design may lead to the introduction of costly practises which are not justified by the ends obtained. This is especially true of a subject as interesting as cavitation. In this connection the writer is unable to agree with the authors' conclusions that European practise, which is to machine and polish all runner blade surfaces in contact with flowing water, is the only logical way to build runners, especially since, as the author points out, such machining or surfacing has no effect on the efficiency. By its very nature this machining of the blade surfaces is an extremely expensive operation and if its sole purpose is positively to eliminate pitting which might otherwise only be slight and easily repaired by welding, then this practise can not be said to be either logical or justifiable.

The New England Power System contains upwards of 500,000 horsepower of installed capacity in hydraulic turbines with heads ranging from 20 ft to nearly 400 ft, including one installation of fixed blade and adjustable blade propeller wheels. Not one case of real serious pitting has ever occurred on the entire system. Such minor pitting as does develop is periodically repaired by welding. Until there is real economic justification for complete machining of the runner surfaces and for the use of expensive stainless steel, the writer believes it would be most unwise to make these practises universal in this country simply because the tendency is in this direction in Europe.

Our pressing need in the furtherance of our hydroelectric developments, especially those with low heads, in competition with steam power, is the reduction of first cost wherever possible. This can only be done by simplification, by careful attention to details of design and construction and by carefully balancing cost against return on the investment before accepting any new practises, however attractive they may appear from a theoretical standpoint.

**L. F. Harza:** The author's paper is a thorough resumé of existing European low-head practise and problems, especially those of turbines and draft tubes.

The reduction in station cost by high speed units of conventional design is confined largely to saving in generator cost, but to some extent also in structure cost.

The higher cost of Kaplan turbines as compared with fixed blade propellers finds its justification in a very much improved efficient range of operation. There is hope that the newly introduced fixed gate, moveable blade Kaplan turbine will much further reduce station structure as well as turbine costs.

American manufactures have lagged in low head and high speed turbine design and there is great need of cavitation laboratories for solution of problems vital to all high speed turbines. The Safe Harbor Water Power Corp. is to be commended for introducing the first one in the United States.

It should be pointed out that the type of station shown in the author's Fig. 22, Vargon, is limited to a head so low that the turbine can be set above head water without exceeding allowable height above tailwater. It is open to question whether the draft head, 14.1 ft, at Vargon does not already exceed the limit of safe draft head for the very high specific speed of 211.

It is an individual problem, as to whether anything is saved by the horizontal installation of the author's Fig. 26. The draft tube problem is complicated, the building width greater, and high tailwater requires design of the generator room walls for outside pressure, and the building as a whole for buoyancy, with drainage pumps to remove leakage.

The daring displayed by European manufacturers in extending the head range of Kaplan turbines to 106.5 feet is commendable and could only be accomplished by the thorough European research complex, and the cavitation laboratories, numerous in Europe.

**James W. Rickey:** In the writer's opinion, the future development of low and medium head hydroelectric projects in the United States depends on obtaining lower plant cost through greater economy in the design of both plant and equipment. Such improved design can be achieved only when the manufacturer and the user of turbines adopt a radically different attitude toward the scientific side of concurrent turbine design and laboratory tests. Heretofore, a lack of engineering knowledge and an unwillingness to incur the expenditure necessary to acquire such knowledge has resulted in unjustifiably increasing the cost of hydroelectric developments. A reasonable amount of money invested in research would often have eliminated expensive operating troubles and also would have reduced the initial investment, thus saving many times the cost of the necessary research.

In the designing of large capacity hydro turbines ignorance regarding cavitation often has been safeguarded by adopting too conservative specific speeds, with the resulting unnecessarily high cost of the power plant but freedom from pitting. On the contrary, in some plants where too high specific speeds were adopted, pitting was excessive and the cost of welding pitted runners, or in some cases the providing of new runners, has been beyond reason; all because of the designer's inability to design for specific conditions runners free from cavitation. These designers deserve much credit for what they have accomplished but the question arises "have they done enough?" The writer believes that the answer is "no" and that if more time be devoted henceforth to the scientific development of new ideas, they should accomplish far more in the next few years than they have accomplished in the past decade.

The author's present and earlier papers on high specific speed turbines indicate one excellent way of attacking the problem of building less expensive and, at the same time, better hydroelectric plants. Of prime importance in this connection is the fact that in the United States there seems to be a woeful lack of appreciation of the necessity for exhaustive theoretical research checked by proper laboratory tests.

In the hope of improving this situation the writer called, in November 1929, a conference of about 30 representatives of hydraulic turbine manufacturers and users to discuss means of providing suitable cavitation laboratories which are essential for a proper study of turbine pitting, there being then several such laboratories in Europe but not a single one in the United States. All attending this conference unanimously admitted that such laboratories are necessary. Today there are a half dozen or more such laboratories in Europe but only one in the United States and that is owned, not by a turbine manufacturer but by a power company! How can our manufacturers hope to develop big propeller or Kaplan type turbines without suitable cavitation laboratories? Some day, in the not too-distant future, the development of the International Section of the Saint Lawrence River will cause orders for approximately 2,200,000 hp of turbines to be dangled before their eyes. Is it not almost axiomatic that the manufacturer who can best prove his ability to deliver the goods will be the favored one?

Looked at from another standpoint, this failure of the hydro turbine manufacturers to provide proper laboratories is, in the writer's opinion, a very short-sighted policy because the steam turbine, coupled with the very efficient boilers now available, is surely giving our undeveloped hydro projects a real "run for their money." Hydro energy from many such projects throughout the country, if developed under today's standards, would cost more per kwhr than if generated by steam and the limit of efficiency in the steam units has not yet been reached. The remedy is obvious.

If the hydro turbine is to compete successfully with the steam turbine in the development of many of our remaining potential water powers there must be a radical improvement in the high specific speed turbine.

The paper presents a valuable resumé of the latest theories, laboratory research and their practical applications. It emphasizes the urgent necessity for much additional work and should be used as a stepping-stone to increase our knowledge along these lines.

**Frank H. Rogers:** In Mr. Karpov's paper, he has described in a very interesting manner the development of propeller and Kaplan turbines and has shown the various steps accomplished and the problems which had to be solved in the evolution from the original slow speed Francis turbine to the modern high speed propeller unit. He has also presented valuable data on the large size Kaplan units recently installed and under construction in Europe.

Mr. Karpov, in giving credit to European engineers for their development work on Kaplan and propeller turbines, has perhaps unintentionally reflected most unfairly on the contributions of American engineers. His statements that "The credit for this past accomplishment was due entirely to European engineers" and "The conditions in the States were unsatisfactory and the turbine manufacturers were unable to make the model tests so essential to the development and proper design of Kaplan and propeller turbines" do not represent the facts.

When in 1921 the Great Falls Development of the Manitoba Power Co. was undertaken, no propeller turbines of over a few hundred horsepower had been constructed, and none had been installed for heads much over 10 or 20 feet. When the Dominion Engineering Works Limited proposed I. P. Morris propeller turbines of 28,000 hp unit capacity for a head of 56 ft, statements were made that propeller turbines would not work under such a head, and some engineers advised that high speed propeller turbines could not be safely used for heads of over 30 ft. The engineers of the Morris Co. at that time developed a cavitation theory for the propeller turbine, utilizing data from marine propeller experience; and on the basis of these calculations proceeded to design the units, which were installed in 1922 and have been successfully operating ever since, and have been followed by additional units of the same design in this plant; and by many other notable installations subsequently carried out. Mr. Karpov in tabulating recent installations includes only one American plant. The total horsepower of American and Canadian installations of I. P. Morris propeller turbines aggregate 876,886 hp, to mention only one company and its Canadian associate. It may be mentioned that very high efficiencies have been secured in American installations of propeller units, such for example as the Dolby plant of the Great Northern Paper Co. (I. P. Morris) giving 93.5 per cent, and the Cumberland County Power and Light Company's West Buxton Station giving 92.1 per cent.

The theoretical basis on which the propeller turbine was made applicable to a large range of heads, and on which its use could be extended with confidence to units of major size, considered the blade area proportions with reference to the cavitation limits imposed by the relation between effective head, draft head and barometric pressure. It was demonstrated that in order to avoid cavitation and to provide stability of operation, the narrow bladed runners of the original Kaplan type, in which the blade area was in the order of one-half of the transverse area of the runner passage, must be abandoned and blade areas must be provided approaching an order of magnitude equal substantially to the complete area of the circular passage or the so-called disk area of the runner. In the face of the earlier teachings that only by a great reduction in area could successful propeller turbines of high specific speed be produced, it was demonstrated that equal or greater efficiencies could be secured by the use of large areas for the blades and that by this means stability of operation and freedom from cavitation could be secured for a head range more than double that which had previously been attempted. This step first proposed by Mr. Moody (an American engineer) is considered to have been one of the most notable advances in the history of the development of the propeller turbine. The theories just mentioned and the results secured by their use were set forth in the paper by Messrs. H. B. Taylor and L. F. Moody presented at the Hydroelectric Conference in Philadelphia in 1922. The development and crystallization of the theory of cavitation were greatly advanced by Dr. Thoma, of Munich, who clearly showed the dimensional relations involved. In his paper on Water Power Research, presented at the World Power Conference in 1924, Dr. Thoma mentioned that "The same result can be obtained from H. B. Taylor's and L. F. Moody's theoretical deductions which were put before the Hydroelectric Conference in Philadelphia in 1922 and which rest upon special assumptions regarding the flow."

In the portion of Mr. Karpov's paper on the design of propeller turbines he describes the importance of making the total area of the runner blades as large as possible in order to reduce the force per unit of blade surface and thus reduce the cavitation danger. He points out, however, that in this type unit the water strikes the blades at high velocity so that an increase in the area of the blades rapidly increases the friction losses and lowers the efficiency. These points were recognized in 1921 when the Manitoba units were built and the difficulty solved in the following manner:

1. A six-bladed runner was adopted with large blade area to prevent cavitation.
2. The blades were designed to reduce velocities of the water with respect to the vane to keep the friction losses within reason. This design results in a circumferential or whirl component of the water leaving the runner.
3. A Moody spreading draft tube was used to regain this whirl component in an efficient manner.

It may be of interest in clearing up the history of propeller turbine development to quote from an article by Dr. Thoma on "Cavitation in Hydraulic Turbines," published in the *Wasserkraft-Jahrbuch* of 1924. Dr. Thoma recapitulates the history of affairs up to that time as follows (freely translated).

"After Kaplan had advanced the suggestion of building turbines with very small vane surfaces and when after the conclusion of the necessary tests the possibility was opened for the practical use of the Kaplan turbine, the danger of cavitation became much more acute. The Kaplan runners looked about like ship propellers with small blade surfaces. The tests at first had only been made with low heads; Kaplan had worked with a head of about 0.6 m and the tests of the Kaplan turbine syndicate had also been made with a head of about 3 m only. The experience with ship propellers and theoretical considerations led to the prediction that at an increase of head cavitation would soon appear. . . . When more than five years ago I first called attention to the danger of cavitation, I met universal unbelief. The general opinion was that this did not happen to water turbines. Today I am blamed in the opposite direction for having judged the sphere of application concerning the Kaplan turbine too small (heads below 5 to 10 m). This criticism is justified, in so far as today propeller turbines with heads up to about 20 m are operating free of trouble, but it is to be considered that my estimate at that time was based on the use of the runner types with very small blade surfaces then employed, and for such types my estimate can today be still considered correct, perhaps even too favorable. That with lower specific speeds (500 to 600) considerably larger blade surfaces can be used whereby the field of application is broadened, no doubt my critics at that time did not know either."

The writer desires in no way to detract in the slightest degree from the importance of Dr. Kaplan's early work in development of the propeller and Kaplan turbines but takes exception to Mr. Karpov's claim for this development as an exclusive European accomplishment. Dr. Kaplan himself frankly admitted his difficulties experienced during this early period, and I might quote from some of his papers as follows.

Writing in the *Wasserkraft-Jahrbuch*, 1925-1926, on "How the Kaplan Turbine Originated," Dr. Kaplan describes his difficulties in a series of tests begun in August, 1921:

"The results of the tests at the laboratory had reached this point when an opportunity offered itself to compare the super-high speed runners in operation with the test results at my turbine laboratory. The appearances mentioned in *Wasserkraft-Jahrbuch* of 1924 then showed themselves, which are called cavitation appearances. The road to the elimination of these appearances was tiresome and connected with many destroyed hopes. Neither I nor my licensed firms knew any solutions as all changes were of no avail. . . . Today, when I review the road of creation of my turbine, I am astonished that the saving idea of the cavitation formation came to me so late, because by this idea all those puzzling appearances with turbines of high speed find their explanation. At that time when the guaranteed tests took place nothing concerning the cause of cavitation was known. In turbine literature there was hardly any mention of it and therefore the bad news kept augmenting which reported an especially large amount of air expulsion and of explosive noises. Neither I nor the engineers could advance any advice. . . . If one examines today a cavitation-free runner, one is surprised why one did not think at once of the simple remedies for eliminating these cavities."

In his description of the modern theories of cavitation phenomena, Mr. Karpov has not mentioned the contributions either of Dr. Thoma or Dr. Spannhake nor the Rogers and Moody paper at the Hydraulic Conference in 1925. In his statement to which the writer has previously called attention regarding model tests, Mr. Karpov is probably referring particularly to cavitation tests. The writer would point out that for several years I. P. Morris Company has been able to avail itself of tests made by its associate company, the Dominion Engineering Works Limited, at the cavitation laboratory of the Shawinigan Water and Power Company at Shawinigan and that through the use of these tests and the study of existing records of plant experience, a large mass of data has been accumulated permitting the reliable design of propeller or Kaplan turbines with either fixed or adjustable blades. The conclusions derived from these data have been quite consistent with the results subsequently obtained at the Holtwood cavitation laboratory. Mr. Karpov has completely ignored notable accomplishments of a number of American engineers working in the propeller turbine field, notably the advances made by Forrest Nagler and the excellent designs and results secured by the S. Morgan Smith Company's engineers in a number of successful installations. The writer has usually found the prominent engineers of Europe willing to give due credit to American engineers for their accomplishments. The writer hopes that claims made on either side of the Atlantic will not be permitted to impair this spirit of fairmindedness and generous recognition of accomplishment.

**James E. Stewart:** Mr. Karpov's paper reaches the logical deduction that propeller type wheels and particularly the Kaplan wheel, will largely supplant the Francis turbine for future low head developments. Accordingly, this discussion will be limited largely to the Kaplan wheel which, except for constant head high load factor loads, probably will be chosen for future installations instead of the fixed blade propeller type.

An interesting point brought out in Mr. Karpov's paper is the academic fact that, other things being equal, the suction drop on the back of the turbine blades is directly proportional to the force applied to the face of the blades. Hence, as brought out in his paper, the avoidance of cavitation depends partly upon keeping down the force per unit of area on the face of the blades; in other words, constructing runner blades with a large total area. However, since the friction loss resulting from large blades is detrimental to efficiency, a nice balance must be struck in determining the best size for the runner blades. No doubt, Mr. Karpov's point that the suction drop on the back of the blade is proportional to the force on the face of the blade, is well known to turbine designers and other students of the subject, but the speaker does not remember hearing or seeing this point brought out in other papers or discussions.

Another interesting point in Mr. Karpov's paper is the fact that for the propeller type turbine the water velocity at the entrance of the draft tube is higher than for the Francis turbine, accompanied by large amounts of water due to low head and large capacity, therefore, the recovery of this larger velocity head necessitates long draft tubes, which in turn are conducive to hunting of the unit. Probably, with the increase in size of American propeller type turbines, the European practise of dividing the draft tube into several sections so as to reduce the size of the moving bodies of water will be followed.

The air-vapor bubble that sometimes forms under certain propeller type wheels is an interesting phenomenon and may be one of the causes of pounding and hunting in certain Francis high specific speed wheels.

Mr. Karpov brings out some interesting thoughts with regard to the use of the propeller type turbine with higher heads. The 76-foot head for the Wettingen development and the 82-106 foot head for the Shannon development are interesting present day developments along that line. If economical and efficient Kaplan turbines can be developed for heads up to say 100 feet, then the Francis turbine can be trusted to economically and efficiently take care of heads from 100 to 1,000 ft and the Pelton wheel for heads higher than 1,000 ft.

It is very probable that we are about to enter a period of extensive low head development with the aid of the propeller type turbines. Not only are there many undeveloped sites where only low head developments can be made economically, but also there are a great number of navigation dams already constructed where the propeller type turbine utilizing syphons or horizontal units may result in very economical developments.

**R. V. Terry:** During the past several years we have been engaged in developing a new type of adjustable vane propeller turbine in which the vanes are adjusted entirely by the flow of water through the turbine, the action being somewhat similar to that of a weather vane. The vanes are pivoted on roller bearings, connected to a dashpot, and provided with means for limiting their angular movement. The vanes are pivoted slightly upstream from their centers of pressure so that the water flow tends at all times to create a relatively small hydraulic moment in the opening direction. This hydraulic moment is balanced by providing a reactive device tending at all times to close the vanes. Experiments have demonstrated that if the vanes are properly proportioned, the reactive moment required to maintain the vanes at the most efficient position will be relatively small and that for a given installation, therefore, for a given speed and diameter of runner, the necessary reactive moment will be substantially constant for varying loads and for varying heads. In other words the vanes of such a runner are automatically adjusted by the water flow to the most efficient angle for any head and for any load within the capacity of the turbine.

In addition to the automatic adjustment during normal operation of the turbine under load, such a runner possesses other interesting features. When the turbine is being started up the vanes assume their maximum pitch position, giving a high starting torque at a small gate opening. As the unit approaches its normal speed the vanes gradually assume the closed position. When the unit is being operated as a synchronous condenser the vanes remain closed.

Outside of the runner the turbine may be of standard construction. No interconnection is required between the runner vanes and the governor which actuates the wicket gates in the customary manner. It is obvious that such an arrangement eliminates much of the equipment necessary for the operation of the usual Kaplan type turbine.

Operation of a unit of this type in connection with a standard governor has demonstrated that the speed regulation is somewhat better than with a fixed blade propeller type. With any appreciable change in either speed, load, or head, the vanes move smoothly to their new position and remain in this position until the conditions are again changed. With small changes in the operating conditions the friction of the mechanism is sufficient to prevent any unnecessary movement of the vanes.

It might be worth while mentioning that we are building a new hydraulic laboratory approximately 36½ ft by 60 ft, three stories high, which will include facilities for studying cavitation of turbine models under head up to 60 ft and draft heads up to 25 ft. The new laboratory will be ready for operation in March 1933.

**F. H. Hollister:** (For discussion see page 188.)

**H. S. Van Patter:** The Canadian Company by which the writer is employed, working in conjunction with a leading United States turbine manufacturer, has designed and built 44 propeller turbines having a total rated capacity of 690,650 hp. These units vary in capacity from 500 to 37,500 hp and operate under heads as high as 68 ft.

The first two of these units, each rated at 28,000 hp under a 56 ft head, were installed in 1922 in the Great Falls Plant of the Manitoba Power Company. Following the Great Falls units, four 30,000 hp turbines under 60 ft head were built for the La Gabelle Plant of the Shawinigan Water & Power Company, and were started early in 1924. While these early turbines have given some trouble from cavitation and pitting, their performance has been distinctly successful, and in all 6 units the original runners are still in service.

Since the initial installation at Great Falls, 4 additional turbines of the same type have been installed. A fifth unit of 32,000 hp rating was installed in the La Gabelle Plant in 1931.

Other notable Canadian installations of propeller type turbines are:

| Power Company | Plant | No. of units | Unit rating | Head |
|---|---|---|---|---|
| Northwestern Pr. Co | Seven Sisters | 3 | 37,500 hp | 66′ |
| H.E.P.C. of Ont | Chats Falls | 8 | 28,000 hp | 53′ |
| Churchill River Pr. Co | Island Falls | 3 | 14,000 hp | 52′ |
| Montreal Island Pr. Co | Back River | 6 | 12,000 hp | 26′ |

The first three of these plants are equipped with fixed blade propeller runners, and the fourth with propeller runners having manually adjustable blades for operation under heads varying from 17 to 28 ft.

All of the Canadian installations referred to above have runners with six blades. The ratio of blade length to blade spacing near the runner periphery varies from 0.75 to unity, the larger values having been found most suitable for the higher head applications. The area of the runner blades is, in all cases, approximately equal to or greater than the disk area between the runner hub and the runner throat. It is interesting to note that recent Europena designs are very similar in these respects and that, for the more critical high head installations, 6 and even 7 blades per unit are now being used.

With reference to the author's remarks regarding the resistance of various materials to pitting action, it has been the writer's experience that a surface welded with chrome nickel steel or chromium steel, and then ground to a smooth finish is very resistant to pitting action. It has been found that plate steel resists pitting much better than cast steel or cast iron, particularly if the cast material has had the finer grained metal near its surface removed by machining. In the writer's opinion a fairly hard tough material, with as fine a grain structure as possible, is most resistant to pitting.

The author states that "for rough approximations it can be stated that the initial cost of the powerhouse, including hydroelectric machinery, for low head developments, is approximately in inverse ratio to the three-halves power of the specific speed." This would mean that if the specific speed is doubled, the cost would be reduced about 65 per cent. In the writer's opinion a variation in inverse ratio of the square root of the specific speed would be much nearer the mark.

**Adolph J. Ackerman:** In spite of the fact that Mr. Karpov's attainments and activities in the field of arch dams have prevented him from having direct experiences on low head hydroelectric developments, he has acquired a thorough concept of the fundamentals and amplified them by reporting on the results of European research, much of which has had little opportunity to become generally known in this country.

The only suggestion which the writer has to offer relates to extending credit to the original investigators and to some of the periodicals or authorities whose illustrations he has reproduced, so that interested engineers may follow up the original references for further study. Furthermore, in the field of turbine design there are still numerous controversial opinions and it is hoped that Mr. Karpov will increase the value of his paper as an authoritative reference by presenting the names of some of the authorities and scientists whose deductions he has presented, such, as for example, the references to the latest theories on cavitation. By presenting the theory of cavitation as announced by Foettinger in 1925, Mr. Karpov has apparently found that this theory is now generally accepted in Europe, but it would have been interesting if he had also made reference to Dr. Thoma's investigations in which he has analyzed in great detail a blasting action which takes place within the pores of the metal as the result of the collapse of minute bubbles which, by calculation may exert a pressure of a thousand atmospheres in mechanically tearing away small particles of metal. This theory would appear to account more readily also for the fact that rough surfaces, which naturally are more porous, fail more rapidly than do polished ones.

In referring to Fig. 22, showing a cross section of the Vergon powerhouse with inverted syphon, Mr. Karpov draws attention to this as a novel development which "opens quite a number of possibilities for similar developments" and he indicates that this feature should contribute to "development possibilities which were considered economically impossible only a few years ago." Since Mr. Karpov's paper is in certain respects a general indictment of American progress in hydroelectric attainments, the writer is urged to point out that the syphon intake is not as recent or novel as Mr. Karpov infers, having been employed in the Green Island Development of Henry Ford & Son, constructed in 1921 and operating under a head of 18 ft. Furthermore, the idea was mentioned in Daniel W. Mead's "Water Power Engineering," page 512 of the 1920 edition, and in earlier editions, where a plant is described as operating under a head of 31 inches and having an inverted syphon intake almost identical to the one described by Mr. Karpov.

# Safe Harbor Kaplan Turbines

## Design of Setting and Cavitation Limit as Developed at the Holtwood Hydraulic Laboratory

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*Synopsis.—The Safe Harbor plant is the first large development in this country to use the Kaplan type of turbine. This paper describes the problems of design and operation which were comprehensively studied by means of model and field tests, with particular regard to the power limits of the turbines as established from a study of cavitation.*

ONE of the numerous features of the Safe Harbor hydroelectric development of more than usual interest is the application of the Kaplan type of automatically adjustable blade propeller turbine. This type of turbine is used in all of the six units of the initial installation, each rated at 42,500 hp. under a rated head of 55 feet. Safe Harbor is the first installation of Kaplan type turbines of large capacity in America, although they have been used for low head developments in Europe since 1919.

At the time of making the decision to use this type of turbine, the largest Kaplan wheel installed in this country had a capacity of less than 5,000 hp. while the largest wheels then designed, were the 38,000 hp. units since installed at the Ryburg-Schworstadt Plant on the Rhine River in Germany.

While the development of the Kaplan or adjustable runner blade turbine has taken place to the greatest extent in Europe, the development of the propeller turbine, particularly the extension of its field to larger powers and higher heads, has been carried out to the greatest extent in America. The availability of propeller turbines for heads over about 30 feet has been due mainly to American engineers.

Many new and interesting problems arose in connection with these Safe Harbor turbines requiring, as with any pioneering development of this magnitude, an unusual amount of experimental and engineering study involving not only the hydraulic and mechanical design of the plant but affecting the structural and electrical design as well.

The limited experience in this country with propeller type turbines, and more particularly with the adjustable blade turbine, caused the management to feel that certain important operating and engineering information was essential to justify a large expenditure in this comparatively new type of turbine. This feeling was intensified by the fact that the manufacturers had to build wheels considerably larger than had ever been built before. Furthermore, the various manufacturers had each offered for our consideration a number of different designs of this type on which no comparative data as to cavitation limitations were available.

The final design of the power house structure rested upon the decision as to the elevation of the turbine runner. The position of the runner with respect to the tailwater elevation would materially affect the power rating of the turbine as limited by cavitation, and obviously the economics of the power house substructure and excavation could only be determined after the power limits of the various runners submitted for consideration was definitely known.

The absence in this country of a hydraulic testing laboratory in which cavitation tests could be made resulted in the construction of such a laboratory at Holtwood, Pa., adjacent to the Holtwood Hydroelectric Plant.

### REASON FOR KAPLAN UNITS AT SAFE HARBOR

During the early engineering studies an investigation was made of the various types of turbines suitable for the Safe Harbor Development which has a relatively low operating head, limited storage, wide fluctuations in river flow and operating head, and where the peak load value of this plant, as distinguished from a base load plant, is of prime consideration.

Appreciable savings in the cost of power house structures were found possible by using the propeller type of turbine of either the fixed or adjustable blade type. Further savings in the cost of the electrical generators were obtainable with propeller turbines due to their higher speeds‡ permitting the use of smaller and consequently lower cost generators and their direct-connected exciters. The following comparison will clearly show these advantages. The Safe Harbor units rated at 42,500 hp. are spaced 62 feet apart while a high-speed Francis type turbine capable of developing the same horse power under the same head would have to be spaced 70 to 75 feet apart; or for the same unit spacing of 62 feet a Francis turbine would be capable of developing only 30,000 to 35,000 hp. which would obviously require power house structures of appreciably

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‡*Hydraulic and Electrical Possibilities of High-Speed, Low-Head Developments*, A.I.E.E. TRANS., 1931, Jessop and Powel.

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larger proportions to obtain the same plant capacity. Again, the speed of the Safe Harbor units is 109.1 r.p.m. whereas the speed of the same capacity Francis turbine, would be only about 60 r.p.m.

The automatically adjustable blade propeller or Kaplan turbine has certain additional advantages over the fixed blade propeller type: a very flat efficiency curve is obtained, it is possible to operate the unit considerably above its normal power rating for short periods of time and without appreciable loss in efficiency, it has materially greater output when operating under reduced heads and is more stable when operating at part load. Due, however, to the additional mechanism required for blade adjustment, the Kaplan turbines are more expensive both in first cost and in maintenance.

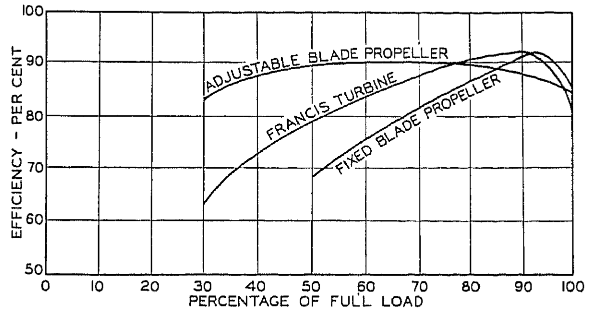

Fig. 1—Comparison Curves for Various Types of Turbines

Safe Harbor unit 42,500 hp., 109.1 r.p.m. (adjustable blade propeller type)
Holtwood unit 20,000 hp., 94.7 r.p.m. (Francis type)
Fixed blade propeller type 40,000 hp., 109.1 r.p.m. 55 ft. head

The relative efficiencies of the Kaplan, the fixed blade propeller and the Francis type turbine are shown in Fig. 1. This curve clearly shows the advantage of the Kaplan turbine for part load operation. The flat shape of the efficiency curve is obtainable due to the fact that the curve shown is the envelope of a series of curves, such as that shown for the fixed blade type, each for a different blade angle. A discussion of the method used in evaluating the power and energy obtainable from the various types and combination of types of units considered, is included in a contemporary paper on Safe Harbor.*

The final decision to use Kaplan turbines in all of the initial units, rather than using one or two Kaplan units and fixed blade propeller turbines for the others, resulted from consideration of the operating requirements of this plant. With a run of river plant such as Safe Harbor where the maximum discharge of the initial six units will be approximately 50,000 cubic feet per second, which flow is available for only about three months in an average year, the plant will obviously operate as a peak load station for the greater part of the time. Such operation involves rapid changes in load. During extreme low flow seasons, when the reservoir will be drawn down on a periodic schedule, a wide variation in the operating head on the plant will be encountered. When the normal river flow is less than the usable flow through the plant, water is valuable for peak service capacity and high operating efficiency at part load is desirable as water thus saved replaces not only steam energy on the system, but increases the capacity value of the plant. High part load efficiencies are particularly important on a system where the spare capacity may be carried at the hydro plants. Furthermore, the Safe Harbor Plant will soon be the point of interconnection of a number of major electrical systems and there will undoubtedly be times when split bus operation will be expedient for considerable periods. With such operation Kaplan turbines are the more economical. Maximum efficiency at full rated load is not essential, as rated output would be required for but short periods during low river flow and at high river flow, when there is an abundance of water, efficiency is not important. Maximum output for short periods and particularly during flood conditions when the back water materially reduces the operating head at the plant is of particular value. Maximum operating economy and flexibility could best be obtained by using turbines all of the Kaplan type. Certain further advantages always accrue through the use of a single size and type of unit in any plant, as it results in a minimum of spare parts to be carried, and minimizes hazards from operation and maintenance.

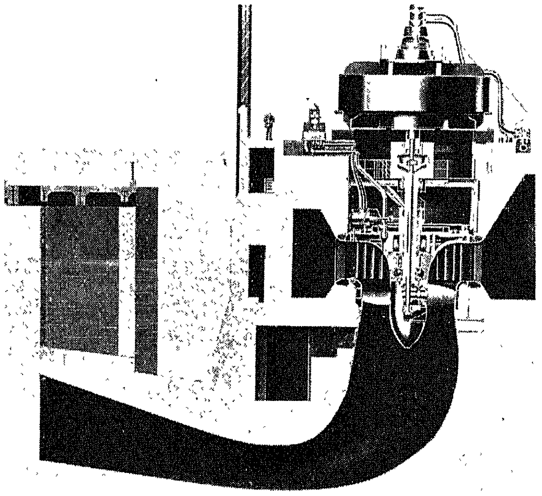

Fig. 2—Cross Section Through Safe Harbor Unit

## Description of Unit

Fig. 2 shows a cut through a Safe Harbor unit. The runner of the turbine is 220 inches in diameter. The runner itself, shown in Fig. 3, has five blades. These blades can be rotated about a horizontal axis from approximately a horizontal position for no-load operation, to an angle of 30 degrees for maximum loads. The blade peripheries and the throat ring are spherically shaped to permit this movement with a minimum of clearance between blades and ring, reducing the amount of leakage from which no energy is obtained.

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**Safe Harbor Project*, by N. B. Higgins, see page 169.

The operating mechanism for changing the blade angle position is shown located in the hub and hollow shafting. Each blade is connected through a link to a main head in the runner hub which is connected by an inner shafting to a large servo-motor located just below the unit thrust bearing. Oil pressure, obtained from the main governor system, is carried to this servo-motor through the Kaplan head (on the top of the generator shaft) from the operating valve shown at the right of the main unit. An actuating rod connects the wicket gate operating ring with this valve to maintain a definite predetermined position of runner blade for each wicket gate opening. This relationship between gate opening and blade angle was found from tests, and is maintained by a specially shaped cam interposed in the actuating rod between the gate operating ring and the runner blade operating valve. This cam may be readily changed for variations in operating head inasmuch as a different relationship is required for each head to maintain best efficiency.

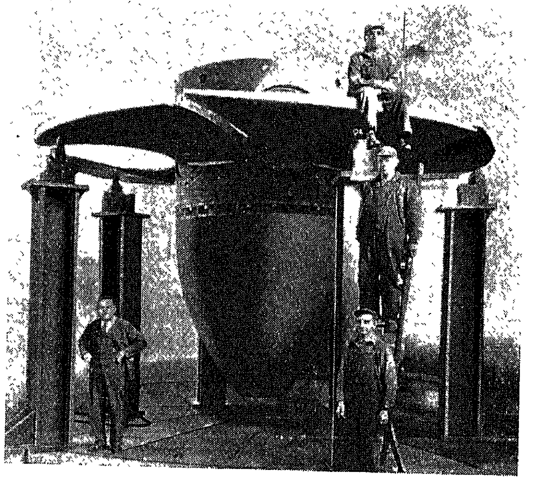


FIG. 3—KAPLAN TURBINE RUNNER

The intake section of the unit has a horizontal floor constructed at the same elevation as the river bottom in the forebay. The side walls are parallel and the roof is bell shaped at the entrance. The center line of the turbine was offset from the center line of the intake 2.0 feet for reasons discussed later.

The elbow draft tube has a *V*-shaped roof toward the discharge end, and there is also an appreciable angle of upturn of the horizontal leg to reduce to a minimum the amount of tailrace excavation required.

### HOLTWOOD HYDRAULIC LABORATORY

The Hydraulic Test Laboratory at Holtwood, Pa., was designed for testing model turbines 16 inches in diameter (approximately 1/14 the size of the actual Safe Harbor units) with complete wheel setting and water passages including intake, scroll case, wheel casing and draft tube, under a range in test head varying from 4 to 60 feet, and for purposes of cavitation tests the draft head may be varied from approximately 10 feet pressure head to 10 feet suction head.

The maximum head at the Holtwood Plant is slightly less than 60 feet, but since, for cavitation tests it is necessary to vary the suction head over a wide range while holding the total head the same, it was found impossible to get the desired range of heads by using the available drop between Holtwood forebay and tailrace. A high head tank therefore was built, into which water can be pumped to an elevation approximately 20 feet above the normal Holtwood forebay, for which purpose a 20,000 gallon per minute constant discharge pump is used. The water in excess of the amount required in the laboratory is by-passed back into the Holtwood forebay by means of a sluice gate operated by remote control from the main laboratory. By manipulation of this sluice gate any desired forebay elevation may be quickly obtained and held constant. From this tank the water flows through a 36-in. penstock to the pressure chamber in the laboratory. After entering, the water must pass through a series of baffles which remove whirls and eddies and insures uniform velocity distribution as the water approaches the intake passages of the turbine. The pressure chamber was designed sufficiently large to permit the installation of the complete wheel setting. The water passes from the draft tube into a vacuum chamber, so called, because a vacuum pump connection permits operating this chamber under both positive and negative pressures, required for the cavitation tests. The water finally discharges through a sluice gate at the bottom of the vacuum chamber, or may be allowed to enter the chamber above the vacuum chamber from which a flume carries it to a sharp crested weir. Fig. 4 is an illustration of the laboratory, with the high head tank and pump house in the background and with the weir and its approach channel in the foreground. Fig. 5 is a cross-section of the laboratory showing the various water chambers and the location of the model setting.

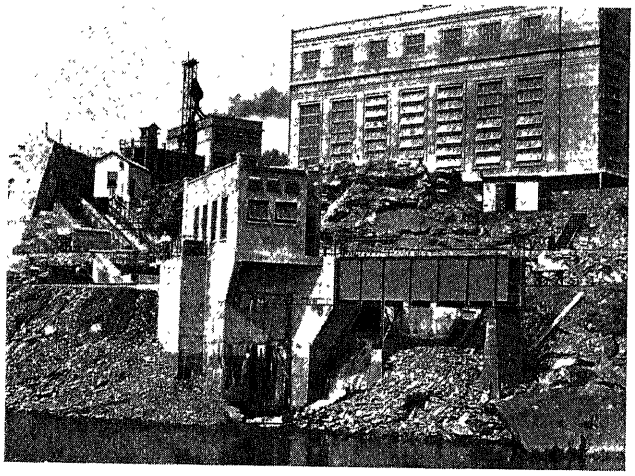


FIG. 4—HOLTWOOD HYDRAULIC LABORATORY

Both the vacuum chamber and the high head tank were designed to permit varying the elevation of the forebay and tailrace over a wide range, yet maintaining the same constant head. Had it not been felt desirable to maintain a constant head for these tests, the high head tank and its accompanying pump could have been omitted.

Because of the wide range required in tailwater elevation, it was impractical regularly to use a weir for measuring the laboratory discharge. A 36-inch by 15-inch Venturi meter was installed in the main penstock for measuring the water flow. The connections to this Venturi meter were brought into the laboratory so that the discharge may be measured in the main laboratory. This Venturi meter was calibrated by Professor C. M. Allen by the "salt velocity" method, and at the same time a calibration was made of the sharp crested weir.

The power developed by the test turbine is absorbed by an electrical dynamometer mounted on the laboratory floor above the pressure chamber, rated at 300 horsepower when used as a generator, but also, for operation as a motor for proposed pump tests designed to develop 225 horsepower. This dynamometer is the first one ever made for vertical mounting and was designed specially for this installation. The electrical power is dissipated in grid resistors located in a separate room at the back of the laboratory.

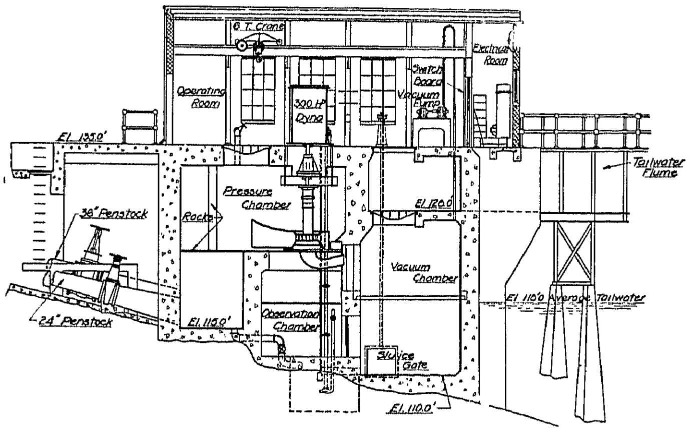


FIG. 5—LONGITUDINAL SECTION—HOLTWOOD HYDRAULIC LABORATORY

To facilitate the study of cavitation, the laboratory has been laid out to permit visual observation of the water flowing in the draft tube, just below the model runner. This has been accomplished by installing small glass windows in the tube. An observation chamber, provided around the draft tube, affords a point of observation for watching the formation of cavitation and the general behavior of water in the vicinity of the runner. There are two methods of determining the cavitation limit of a turbine. In the first method the presence of cavitation is detected with the eye using a stroboscope, an instrument for cutting the moving wheel from vision through a large part of a revolution so that in effect the eye appears to see the revolving wheel as though standing still. With this instrument, it is possible to observe the formation of the vacuum pockets on the surface of the blade. The water leaving the tips of the blade will have a milky appearance when cavitation is present. There are however, several reasons why it is impractical to accept the visual method alone in determining the operating point at which cavitation begins. The more accurate method used consisted in making a series of tests for varying values of draft head on the runner, while maintaining the speed and the total head the same. A graphical analysis of these test results permits a more exact determination of the point at which this cavitation phenomenon is present.

## CAVITATION LIMIT OF TURBINE

As has been previously stated it is of utmost importance to locate the turbine runner at the proper elevation with respect to the tailrace surface. If any type of waterwheel is located too high above the tailrace, the vacuum formed under the runner blades may cause cavitation. This phenomenon is common even with Francis wheels, and due to the higher velocities present in propeller turbines there is even greater danger of cavitation. The result of cavitation, in addition to serious loss of efficiency, is the destruction of the runner and draft tube by pitting. Pitting is probably due to the combination of erosive and corrosive action. Cavitation starts when the absolute pressure at any point in the water column approaches the vapor pressure of the water, which pressure is, of course, very near absolute vacuum. In most high-speed turbines, either of the Francis or propeller type, the maximum velocity takes place as the water passes through the runner. The greater tendency towards cavitation in a propeller runner is caused by the much greater relative and somewhat greater absolute velocity in combination with smaller blade areas. The exact location of the minimum pressure depends upon the design. If this low pressure falls below the vapor pressure at any point along the blade surface, the water will no longer follow the blade curvature, but will have a tendency to leave the surface of the blade forming a void. The voids will quickly be filled with a mixture of water vapor and air, removed from the adjacent water by "cold" boiling. The surface of separation between the flowing stream and the eddying region left by the separation, may be shown theoretically to be essentially unstable. Hence, sudden breakdowns of the cavities rapidly recur, having the effect of continuing explosions, resulting in intense water hammer action in the pores of the metal. It is this sudden collapse of these many minute bubbles, accompanied by the resulting impact and vibration which is so destructive to the adjacent metal parts. Eventually such action erodes the surface of the runner blades. In addition to this erosion it is probable that oxygen, which is readily released from solutions at very low pressures accumulates along the surface of the runner blades, and attacks the steel surfaces, especially where the metal has been previously attacked by erosion.

Cavitation can be practically eliminated by setting the runner sufficiently below the tailwater level to insure that the minimum pressures along the blade surface are well above the vapor pressure. For economic reasons it is very important to determine accurately the maximum elevation that the runner may be set, to reduce to a minimum the expensive excavation work for the draft tube and tailrace.

Tests on a complete model of the Safe Harbor intake, scroll case, wheel setting, runner, and draft tube were made to determine within very close limits the highest elevation at which the runner could be set without danger of serious cavitation for the maximum turbine power desired. Fig. 6 shows the results of a typical test made in determining the value of draft head at which cavitation starts. The efficiency, power, and discharge of the turbine have been plotted against the coefficient sigma. The term "sigma," first introduced by Professor Thoma of Germany, is derived as follows:

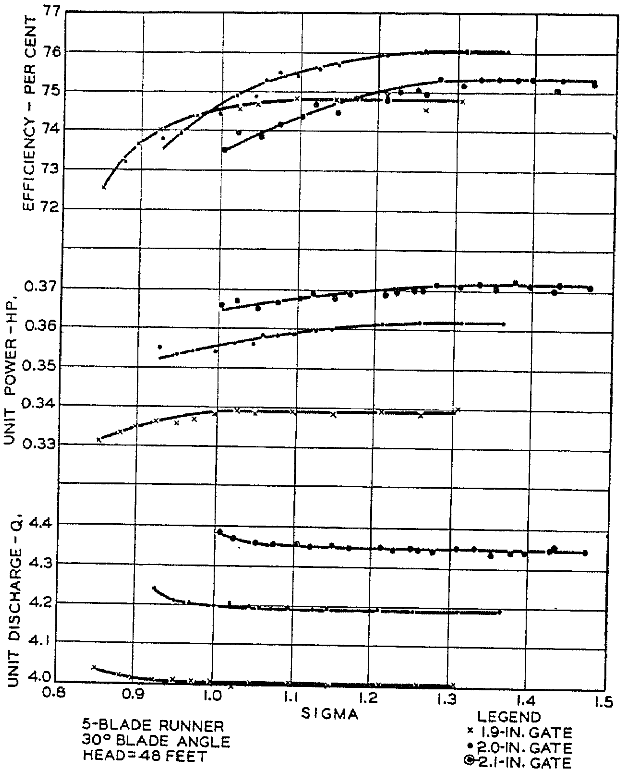


Fig. 6—Typical Cavitation Curves of Test Results

Theoretically, cavitation starts when the absolute pressure on the runner is equal to the vapor pressure of the water, therefore

$$H_B - H_D - \frac{\Sigma V^2}{2g} = H_V \qquad (1)$$

$\frac{V^2}{2g}$ varies directly with $H_T$

Therefore (1) may be written

$$\Sigma = \frac{H_B - H_D - H_V}{H_T} \qquad (2)$$

Where:

$H_B$ = barometric pressure in feet of water at the surface of the tailwater
$H_V$ = vapor pressure of the water
$H_D$ = draft head (elevation of runner minus elevation of water surface in tailrace)
$H_T$ = total net head on the runner
$\frac{V^2}{2g}$ = velocity head at the blade surface
$\Sigma$ = coefficient

The laboratory procedure in determining the cavitation limit for a definite blade angle and gate opening was to start out with a high tailwater elevation and make a series of tests with gradually decreasing tailwater level, maintaining for each series of these tests constant total head and a constant speed. The efficiency-sigma, discharge-sigma and power-sigma curves were developed over a range in sigma values from a constant condition of efficiency, power and discharge, to one in which a material change in discharge and efficiency occurs. The value of sigma at which efficiency and discharge were found to break, was taken as the cavitation limit for that particular speed, head and gate opening. Similar tests had to be carried out for each combination of head, gate opening and blade angle. From the results of these tests it was possible to predict the cavitation limit of the prototype for various operating combinations of draft head and total head. From an operating standpoint it was essential to establish the limits of power output for a wide range in both draft head and total head.

## Model Tests of Draft Tube Design

Correlated with the study of the cavitation limits of a turbine, and the economics of determining the proper runner elevation, is the problem of draft tube design. A draft tube which is designed with the shortest vertical section will usually be the least expensive, as a minimum of excavation will be required not only under the power house substructure but also in the tailrace area below the power house.

In the light of European experience, together with theoretical considerations of the water velocities through a Kaplan runner which indicates that the tangential velocity component in the water as it leaves the discharge edges of the runner blades even at part gate, would be relatively small, which tangential velocities would best be recovered in a spiral type of tube; together with due consideration of the somewhat higher construction costs for this type of tube, led to a decision in favor of an elbow type, even though an additional amount of rock excavation was required.

The turbine manufacturers each submitted alternate designs of elbow tubes which were all tested in the Holtwood laboratory with the Safe Harbor model runner, to obtain comparative data on the relative efficiencies and operating characteristics. These tubes differed in the following general features of design:

1. Angle of flare in the vertical section just below the runner.
2. Length of the vertical section (distance between center line of runner and lowest point of the tube).
3. Location and area of the draft tube "throat."
4. Shape and angle of divergence near the discharge end of the horizontal section.

The final design chosen, was determined not only from a consideration of the maximum efficiencies obtained, but also with due regard to the shape of the horsepower efficiency curves, in order to obtain a curve as flat as possible for each blade angle position, thereby eliminating any possibility of instability resulting from sudden changes in load, when the gate opening of the unit might suddenly change without an immediate response of the blade angle mechanism, which latter consideration was felt to be important. A certain amount of actual operating experience available at the time, on the final design chosen was also given due consideration in making the final decision.

After deciding on the general design of the tube to be used, further studies were carried out along three lines: first, the determination of the most economical length of the horizontal section of the tube, second, the determination of the maximum upward turn of this horizontal leg which could be considered without sacrificing efficiency, and third, the determination of the proper area at the discharge end of the tube.

The results of the first of this group of tests indicated that a longer tube than was actually decided upon would have shown higher values of power and efficiency, but it was feared that using a lengthy horizontal section might result in the same regulating difficulties encountered in the use of long penstocks.

The second group of tests on the final tube was made for the purpose of reducing to a minimum the excavation in the tailrace area. A very appreciable amount of excavation was saved by turning this whole tube upward through an angle of 9 degrees without sacrificing either efficiency or power. Tests were made using even greater angles of upturn but the loss in efficiency did not appear to warrant the savings in excavation.

The third group of tests was carried out on modifications of the angle of divergence of this tube as shown in Fig. 9, which also clearly indicates the relative dimensions of the tube, the angle of upturn and the shape of the discharge section. Dimensions shown are for the model tube used in the laboratory. Fig. 10 shows the assembled form work for one of these Safe Harbor draft tubes. A plate steel draft tube liner was used as a form for the upper part of the vertical section.

## Model Tests of Scroll Case Design

A series of scroll case tests was made in the laboratory, before deciding on the final design, in order to determine whether any advantage is realized by offsetting the center line of the runner shaft from the center line of the intake, thereby increasing the cross-sectional area of the scroll and reducing the velocity of the water. The results indicate that if, for the unit spacing used at Safe Harbor, a speed ring with a relatively large diameter were used a very noticeable saving in efficiency and power could be obtained. If, however, the fixed guide vanes of the speed ring were of narrow proportions and the speed ring of smaller diameter, there was no improvement found in either efficiency or power.

The scroll case of the Safe Harbor turbines were, however, designed eccentric even though the overall diameter of the speed ring was relatively small, this decision being made to give a maximum of flexibility in the design of the wheel settings for all future units for this plant.

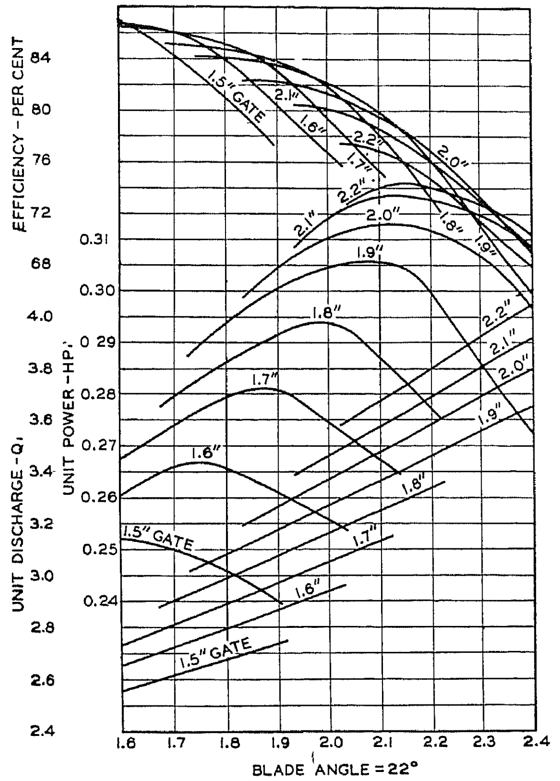


Fig. 7—Typical Efficiency Curves of Test Results

## Power and Efficiency Tests

All turbine manufacturers were asked to submit with their guarantees of power and efficiency, the test results obtained from a model of the runner which they were submitting for consideration at the Safe Harbor Plant and on which these guarantees were based, as it was felt that a comparison of these test results obtained from the same size models was of greater value than a comparison of the actual guarantees. Unfortunately, however, these tests were of course made in the laboratories of the different manufacturers and it was later realized that a fair comparison of such tests could not be made. This, it should be pointed out, is no reflection on the laboratories but merely an honest recognition of the difficulties encountered in obtaining an absolute calibration in special commercial laboratories of this type. Such a comparison was further complicated by the fact that certain manufacturers were unable to make tests on a gross head basis, as the laboratory was not designed to permit the use of a model intake and scroll case.

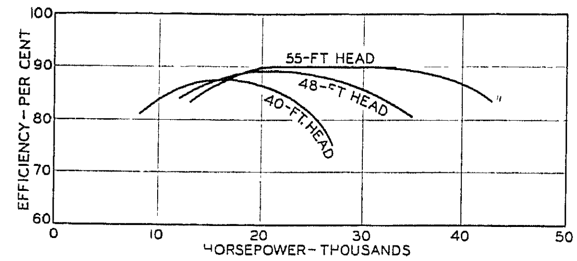


FIG. 8—GUARANTEED HORSEPOWER EFFICIENCY CURVES—SAFE HARBOR UNIT

Safe Harbor development guaranteed horsepower efficiency curves. Gross heads of 40 ft., 48 ft., and 55 ft. Five blade Kaplan turbine; speed 109.1 r.p.m.

Comparative power and efficiency tests on each of the numerous turbine designs submitted were therefore made at the Holtwood laboratory, all tests being made with a complete turbine setting, including intake, scroll case and draft tube. These tests were made under a test head approximately equal to the field head existing at Safe Harbor of about 50 to 55 feet, and in each case was made in the presence of a representative of the manufacturer whose runner was under test. At the completion of these tests the manufacturers were given the opportunity to revise their guarantees of power and efficiency on their respective turbines. Fig. 8 shows a portion of the guarantees for one group of the Safe Harbor units.

A curve sheet giving the results of a typical test, is shown in Fig. 7. The range in the values of $\Phi$ covered, corresponds to a variation in head of from 32 to 60 feet, although the actual testing was done under a constant head and varying speeds. Tests were made at various blade angles to develop an envelope curve representing the maximum efficiency obtainable for the proper operating relationship between blade angle and the wicket gates, which relationship is maintained on the actual units as previously described by means of a cam in the blade operating mechanism.

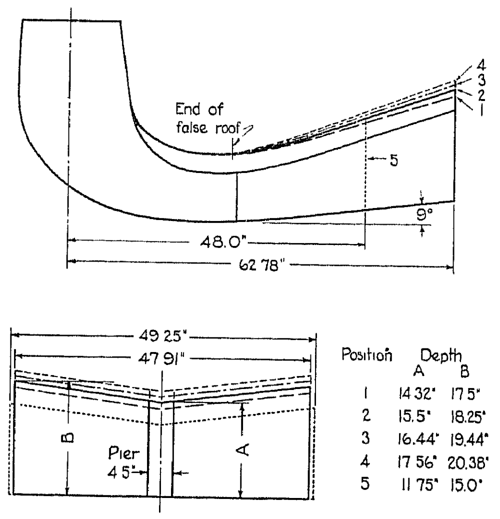
These cams were designed from the data obtained on the model runners, and it has been found from actual field tests that only minor reshaping of the cam was necessary to obtain the best operating efficiencies.

During these power and efficiency tests, it was found that on certain gate openings a vortex was formed near the bottom of the deflector or the hub of the runner. This vortex was readily observed through the windows of the model draft tube, and was found to occur over a wide range of test conditions, although not in the normal limits of field operation. It was feared however that this vortex might appear in the Safe Harbor turbines although it has not been detected up to this date. This same phenomenon is undoubtedly the cause of hydraulic instability at part loads of a fixed blade type of turbine, which frequently results in unsteady operating conditions and serious difficulties when attempting to synchronize.

## FIELD TESTS

To insure that the units are properly adjusted and are operating to give the best possible efficiency, numerous field tests and inspections were planned. A certain amount of cavitation is probably permissible since the steel blades of the turbine will resist a considerable amount of shock and it was decided to operate the units slightly beyond the point where cavitation started in the laboratory, and carefully study the effect on the runner blades and draft tube.

During the first few months of operation the turbines were carefully inspected about every two weeks. Now that the plant has been in operation some time, these inspections occur about every six weeks on each unit. It has been found that on certain portions of the runner blades, paint was removed. There is a small area on both the top and bottom surface at the leading edge near the periphery, which seemed to be subject to local cavitation. Very small hollows and reversals in curvature attracted cavitation, and eventually pitting took place. The original design of the leading edge called for very slight rounding of the corners only, with very little reduction in thickness of the blade. Probably this local cavitation was caused by the impact of water impinging on the blunt nose and forming eddies, and a low pressure area just back of the leading edge. By slightly reshaping the leading edge so that it was sharper, and making a



| Position | Depth A | Depth B |
|---|---|---|
| 1 | 14 32" | 17 5" |
| 2 | 15.5" | 18.25" |
| 3 | 16.44" | 19.44" |
| 4 | 17 56" | 20.38" |
| 5 | 11 75" | 15.0" |

FIG. 9—VARIOUS DRAFT TUBE MODIFICATIONS STUDIED

very gradual transition from the nose to original blade surface from six to eight inches back from the leading edge, this local cavitation was largely eliminated. This area will probably always be susceptible to cavitation, and consequently, it is of the greatest importance to have a very smooth surface, free from reversals in curvature. One unit was held at a power output limit well below the point where cavitation started on the model. The paint erosion on this unit was less than paint erosion on the other units, but the local pitting mentioned above was of about the same magnitude, and in the same place.

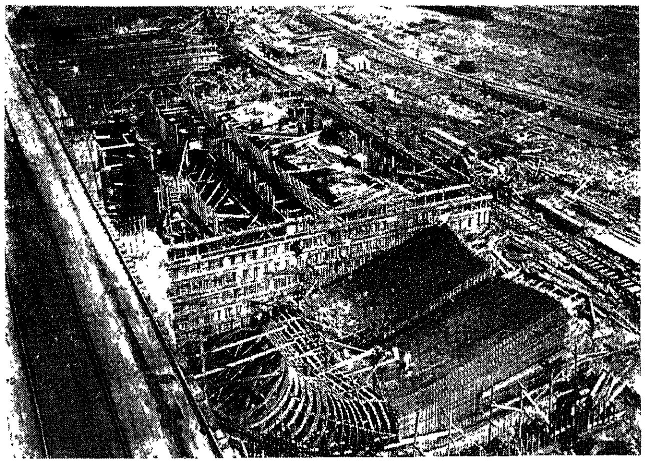


Fig. 10—Form Work of No. 7 Unit at Safe Harbor

On the underside of the blades near the trailing edge, an area has been attacked by a very slight cavitation of a magnitude sufficient to remove the paint, but as yet there is no indication of pitting. It is interesting to note that rust has covered these areas in spite of the cavitation.

To establish the most efficient relationship between gate opening and blade angle, it is not necessary to measure the actual efficiency or discharge, and it was decided to establish this relationship by the use of an index method. Seven piezometers were therefore installed at various points in the scroll case and on the wheel setting during the construction of the plant. At the time of the turbine efficiency tests these piezometers will be calibrated and a meter will ultimately be installed to integrate as well as indicate the discharge through the turbines. It is proposed to have a meter on each unit and a totalizing meter will be located in the control room to indicate the total discharge through the plant.

The usual methods of testing hydroelectric units used in this country have been found inadequate on most low-head developments where large quantities of water are to be measured, due to the shortness of the approach passages to the unit. In Europe, current meters have been used for a number of years in making efficiency tests, and have been found particularly adapted for use on low-head developments. A number of turbine efficiency tests has been made in this country with current meters, but on such tests, only a few meters were employed, and the results have usually been of doubtful accuracy. It was decided at Safe Harbor to follow the European method of making current meter tests and to employ the Ott meter so generally used abroad.

One difficulty encountered in making current meter measurements is the time required to traverse properly the area of the metering section. It was found that a large number of metering points would be necessary for each horizontal traverse. Twenty-seven current meters were therefore purchased of the spoked-wheel type and all mounted in the same horizontal plane on a rack made up of stream line rods. This rack can be lowered in the gate slots to any desired elevation for obtaining a vertical traverse.

It was recognized that the Ott spoked-wheel current meter consistently under-registers for angular flow. The metering section, at the gate slots is just at the end of the bell-mouth so that there obviously would be considerable angular flow near the top of the metering section. It was felt that by using another type of current meter which gave a greater degree of under-registration for angular flow it would be possible, by proper calibration, to determine the actual angle of the stream flow from the difference in velocities obtained by these two types of meters, and true velocity could be computed. For this purpose Dr. Ott of Germany recommended a conical screw propeller meter which under-registers to an even greater degree with angular flow than the spoked-wheel type. It was found that the difference between the indicated velocities of these two types of meters increased uniformly with an increase in the angle of flow so that for a given difference

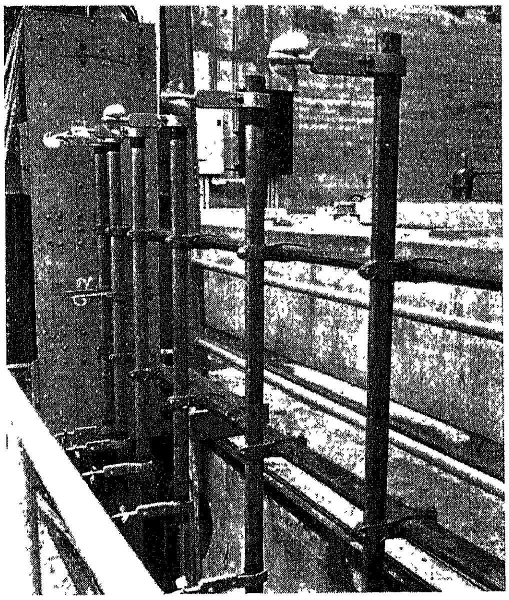


Fig. 11—Current Meter Rack with Meters in Place

in observed velocity on the two types of meters the true angle of flow was readily determined and a proper correction could be applied to obtain the true velocities passing the metering section.

Twenty-seven additional conical screw propeller current meters were therefore purchased and mounted on the same current meter rack six feet above the spoked-wheel meters. Fig. 11 shows a portion of one of these racks with the two types of meters in place.

### CONCLUSIONS

The test program as carried out in coordination with the plant design has resulted in numerous improvements in operating performance, saving in construction costs, and has permitted a more complete study of the behavior of these units. Such a program eliminated to a large degree the necessity of relying too greatly on the very limited field experience available. No little part of the success of this program is due to the efforts of the engineers of the two turbine manufacturers who, to a greater extent than ever before in the hydroelectric development of America, cooperated to build turbines of identical hydraulic and mechanical design wherein practically all replaceable parts are interchangeable.

The first six-month period of actual performance indicates that the prediction of the cavitation limits for the turbines based on the laboratory model test results is reasonably close, although a considerably longer period will be necessary to establish definitely a close correlation between laboratory and field results.

Turbine efficiency acceptance tests have not yet been completed.

## Discussion

**E. Brown:** The account of experimental work carried out at the Holtwood Laboratory shows that operating companies are fully convinced of the importance of testing of turbine models, especially in connection with projects of such magnitude as the Safe Harbor development. The conditions of operation at Safe Harbor are fundamentally different from those found in Canadian projects, in which many propeller turbines of output up to 37,500 hp have been installed in the past few years for heads as high as 65 ft. The reasons for the adoption of the Kaplan type of wheel at Safe Harbor, are made clear by the authors, and as the preliminary experimental work has evidently been carried out with great thoroughness it will be interesting to relate the experiences of actual operation with the expectations based on tests of models.

The authors point out the importance of a study of the efficiency, unit power, and unit quantity, in their relation to the cavitation factor, as determining the elevation of the runner in relation to the tailrace—a factor which obviously influences greatly the economics of any project.

Some typical curves for a head of 48 ft are shown in Fig. 6. It would appear, however, that these must refer to some condition not paralleled in the large units, because the highest efficiency shown is only 76 per cent, whereas Fig. 8 shows expected guaranteed efficiencies for the S. Morgan Smith wheels as ranging from 80 per cent to 89 per cent for that head. Possibly Fig. 6 refers to some speed other than normal. The curves in Fig. 6 show large differences between the values of sigma at which the efficiency begins to decrease, and the unit quantity to increase. Thus for the gate opening 2.1 in., the efficiency begins to decrease at sigma 1.3, whereas the unit quantity does not increase until sigma = 1.1. The points of increase or decrease are not well defined, and this is frequently the case in such tests. The authors do not state whether the draft head was measured to the elevation of the trailing tips of the runner blades, or to some other elevation of the runner, so that the distance from trailing tips to tailrace level for any given value of sigma is uncertain. A difference of 0.2 in the value of sigma, as noted above, corresponds however to a difference of 9.6 ft in suction head, when the operating head is 48 ft. Even if the so-called "breaks" in the curve were estimated to be closer together than as stated above,—so that the sigma difference is only 0.1—the corresponding difference in suction head would be 4.8 ft. This is a large amount, representing 10 per cent of the operating head in these tests. Possibly the form of the curves for tests giving higher efficiencies showed sharper breaks at sigma values, more nearly equal than those referred to above. The authors' statement that "the value of sigma at which efficiency and discharge were found to break, was taken as the cavitation limit for that particular speed, head and gate opening" would seem to imply much closer agreement between sigma values than that shown in Fig. 6. Some additional information on this point would be welcome.

The authors state further that in cavitation tests it is necessary to vary the suction head over a wide range *while holding the total head constant,* and special pumps were installed to control the headrace level to fulfill this condition. The writer is not aware that the necessity for constant head has been fully established, and it would add greatly to the value of the paper if some definite data could be given to show the differences in efficiency, unit power, and unit quantity obtained at a given sigma: (*a*) under constant head; (*b*) under a head controlled only by changing tailwater level. The large units themselves are apparently expected to operate under variable head, say from 40 ft to 55 ft as shown in Fig. 8, and in practise the variations in tailwater level are frequently greater than in headwater level. The conditions are of course governed by many factors, and particularly by considerations of peak-load operation in which the level of the headrace pond may be drawn down considerably in a short time. Curves of the type shown in Fig. 6 have been obtained by the writer in experimental work similar to that described by the authors, but with approximately constant headrace level, and have been used successfully in connection with the installation of large propeller turbines having fixed blades. It would seem, however, that the authors regard constancy of head as of great importance. It would be interesting to know how it has been established that results of cavitation tests made at constant head are more directly applicable to conditions existing in an actual plant in which the head varies, than are the results of tests made at the same values of sigma when these are obtained by varying the tailwater level.

It may be well to draw attention to the fact that extremely low pressures do not release *air* from the water, if by air is meant oxygen and nitrogen in the proportions found in the atmosphere. The solubility of oxygen in water is greater than that of nitrogen, and the gases released are relatively richer in oxygen than is the atmosphere from which those gases are derived. The possibility of this greater oxygen content being favorable to certain actions which might contribute to pitting should not be overlooked.

The authors refer to the difficulty in measuring the quantity of water used in low head plants owing to the shortness of the water passages, and their experiences in the use of the European method of metering will be welcomed. The writer first used the Ott method some years ago under similar conditions, and believes that it offers many advantages.

It is hoped that when experience in operation of the Safe Harbor plant is sufficiently extended, the authors will present the results in their relation to the expectations based on the Holtwood tests, and thus contribute greatly to our knowledge of hydroelectric practise at low heads.

**J. A. Peck:** The writer is one of those who, by virtue of lack of personal contact with the interesting phenomena of cavitation, is not very clear as to some aspects of the investigations referred to in the paragraphs on this subject. Was the efficiency test method, for determining the point at which cavitation begins, considered more accurate because the efficiency break occurred before the milky condition of the water became visible by means of the stroboscope, or because the break occurred at a value of sigma which was part of a relatively wide range of sigma values, over which the cloudiness was visible but showed no critical condition? Were the limiting values of sigma chosen at the break for the sake of efficiency maintenance or was there an expectation, at the time of these investigations, that a cavitation condition, existing at sigma values where no adverse effect on efficiency was apparent, would not be seriously destructive to the runner blade? What means were employed to isolate the phenomenon of the efficiency break so that it is positively attributable to the cavitation rather than to some other coincidental factor, such as a crisis in the flow conditions within the particular type of draft tube in use?

The writer had hoped for a more complete treatment of the use of flow index methods, but realizes that a great deal of work can be expended in analysis of such investigations and trusts that they may be the subject of a later paper.

In the choice of draft tubes it is remarked that, while a longer tube than that chosen would have shown higher values of power and efficiency, it was feared that regulating difficulties might result. This recalls similar doubts in regard to the great horizontal length of the tube installed at the Bellows Falls plant of the New England Power Association. The choice here was limited to a long and narrow tube by the fact that the entire tube and most of the wheel setting was to be excavated from ledge, so that each tube became a special form of concrete lined tunnel. The horizontal length from the shaft center line to the mouth of the tube was 100 feet.

This tube was investigated in tests made at the S. Morgan Smith Company in 1927 and described in the 1930 report on Draft Tube Tests by the Hydraulic Power Committee of National Electric Light Association. The model has a throat diameter of 16 inches, while the prototype diameter is 14 feet, 5½ inches, a ratio of 1 to 10.83. According to the system of proportions adopted for the test report referred to, using the throat diameter as unity, this tube has a depth of 2.99 and a horizontal length of 6.88. By scaling the Safe Harbor tube in Fig. 9, it appears that the longest tubes have a depth of 2.05 and a horizontal length of 3.85.

In general, these model tests agree with the authors' results, that the longer tube yields greater capacity and higher efficiency and that the mouth may be raised without sacrificing either. In elevating the mouth of the tube, however, it was found that, if the slope began too near the bottom of the curved elbow, a decided loss was incurred. The tube adopted retained a level floor about half way from the elbow to the mouth, then sloped abruptly upward at an angle of about 11 degrees.

This plant has been in operation for over three years and is one of the automatic frequency regulation centers. As far as effects traceable to the draft tube are concerned, regulation has been entirely normal. The salt velocity test, made by Professor C. M. Allen of Worcester Polytechnic Institute in 1929, showed a maximum net efficiency of 93 per cent.

**L. B. Stirling and J. B. MacPhail:** This paper is a valuable addition to the literature of tests on hydraulic models. The work which it describes must have saved a great deal of uncertainty in matters which are beyond computation, and one may expect that experience in operation of the units will again show the value of this method of determining the most suitable equipment for new conditions. The designers of the model plant are to be congratulated on the extent of the facilities which they have provided for this work.

The writers have been engaged, under direction, on some similar work on propeller runners at the testing plant of the Shawinigan Water and Power Company, at Shawinigan Falls. The plant was built some nine years ago, before sigma had been heard of, but it has been found suitable for certain cavitation and efficiency tests, the results of which have afterwards been confirmed in operation.

The curves in Fig. 6 do not show the sharp break which is supposed to indicate definite cavitation, and it would be desirable to know at what points on the sigma curves the cavitation limits were considered to occur. It might be mentioned that the models tested at the Shawinigan plant showed little drooping, even with values of sigma as low as 0.52, but this, of course, is largely a characteristic of the runner.

We would like to know also, whether the possible occurrence of draft tube pitting was examined by paint tests. There is believed to be a good relation between pitting of a painted surface in a model draft tube, and erosion of concrete on the full size installation; that is, a model which shows no pitting of such paint will probably show no erosion of concrete on natural scale. This relation has proved to be correct in two cases at least, and it may be provisionally assumed to be true in other cases where the models have not actually been built in full size.

The relation between the efficiency of a model turbine and that of a homologous unit of a larger size is given in a paper presented before a meeting of the American Society of Civil Engineers in 1925 by Mr. Moody. It would be interesting to know whether the manufacturers base their guarantees exactly upon this formula or, if not, what margin they allow in order to protect themselves against the possibility of their turbines not operating exactly as calculated.

The writers were very interested to note that the Safe Harbor turbines are to be tested by means of current meters and it is to be hoped that the details of these tests will be made available to the profession. The Shawinigan Water and Power Company has been making turbine tests with current meters for several years and the results have been quite satisfactory. This method of testing has advantages over other methods now in use in that it interferes very slightly with the normal operation of a plant and the amount of preparatory work required is very small.

The authors of this paper are to be congratulated on the work which they have done and the manner in which it is presented in this paper. It is to be hoped that the study of turbine characteristics will be continued at this plant, as it appears that the most rapid advance of the art of turbine design will be made through the use of this and other similar plants.

**R. E. B. Sharp:** During the cavitation tests of some of the models tested at the Holtwood Laboratory, the writer observed, through the openings in the draft tube, that cavitation often existed along the trailing portion of the runner blades nearest the hub. The writer thinks he is correct in saying that this condition could be seen before the cavitation limit, as indicated by runner performance, was reached, but would like Mr. Davis's corroboration on this point. The cavity formed at this part of the runner was doubtless caused by the necessarily increased blade thickness near the hub, and by fillets which are necessary from stress considerations, where the blades join the hub. This cavitation appeared to be continuous, and to extend over an appreciable portion of the blade upstream from the trailing edge. The testing of the runners at and above the cavitation limit produced pitting on the blades, but although the cavitation was actually visible at this part of the blade, no pitting was observed on the blade surfaces.

The cavitation test data clearly demonstrate that with a given value of sigma and a given amount of power developed, the tendency to cavitate increases with phi, or in other words, with the velocity of the blade surface. Nevertheless, the writer would like to find a clear explanation and reason for actual cavitation being more effective in producing pitting at a high blade velocity than where such actual cavitation exists, but with low blade velocity.

An installation in Canada furnishes an interesting example of the ability of a turbine to operate without serious pitting, with a value of sigma so low as to result undoubtedly in the formation of continuous cavitation without sufficient pressure to cause the collapse of the cavities. Fig. 1 shows points representing the installations noted, plotted between sigma as the ordinate and specific speed as the abscissa. A line has been drawn along several of the lower points as representing roughly the limit in sigma for the usual modern propeller runner designs.

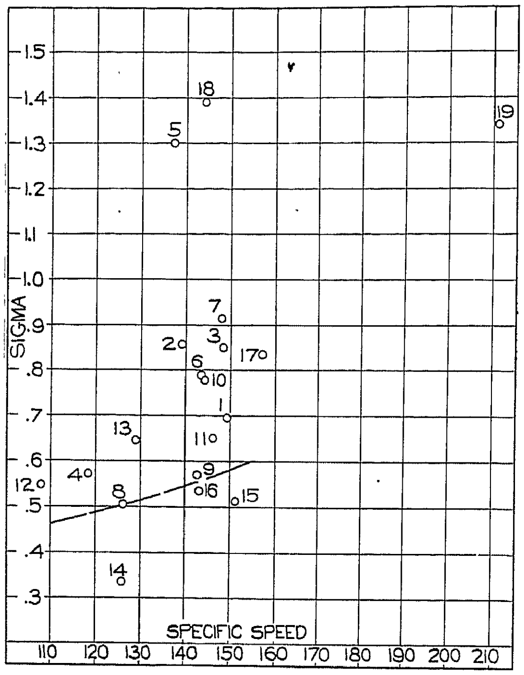


Fig. 1

| No. installation | Hp. | Hd. |
|---|---|---|
| 1 Safe Harbor | 42,000 | 55 |
| 2 Beebee Island | 5,000 | 30 |
| 3 Beebee Island | 5,700 | 30 |
| 4 Dolby | 3,900 | 48 |
| 5 Anson | 1,500 | 20 |
| 6 Slave Falls | 500 | 30 |
| 7 Slave Falls | 12,000 | 30 |
| 8 Churchill | 14,000 | 56 |
| 9 Seven Sisters | 37,500 | 66 |
| 10 Hydro El. Pr. Co. | 5,000 | 36 |
| 11 Chat Falls | 28,000 | 53 |
| 12 Maribondo | 5,000 | 59 |
| 13 La Gabelle | 32,000 | 60 |
| 14 St. Albans | 4,000 | 64 |
| 15 Manitoba | 28,000 | 56 |
| 16 Mixnitz | 12,150 | 64.4 |
| 17 Ryburg | 37,700 | 38.7 |
| 18 Lilla Edet | 11,200 | 21.3 |
| 19 Vargon | 15,200 | 14.1 |

Admittedly, this method of plotting these points is not altogether sound, as the value of phi and the blade area is not considered. The Canadian installation mentioned is point No. 14, with a value of sigma of 0.334, where for this value of specific speed (126) the curve of minimum sigma values passes through sigma equals 0.503. No information as to the efficiency developed by this turbine is available. However, it has operated for more than three years without noticeable pitting, under a total head of 64 ft. This is a propeller type, six-blade runner, stepped from the same model as the runners in the 28,000 hp Manitoba units (point No. 15), and the runner in this turbine replaced a runner (incidentally of foreign design) which did not stand up at all against the pitting action.

In this case, there was no choice, of course, but to accept the limitations as to diameter, the existing value of sigma and the specific speed. Naturally, for a new development such a value of sigma would not be considered. Nevertheless, the performance of this replace runner indicates that the carrying of the sigma curves to values far below the initial break in the performance curves might show unexpected results. In this case continuity of flow is undoubtedly completely destroyed for some distance below the runner, with attendant loss of efficiency as represented by the actual loss in head. On the other hand, the water probably is entirely clear of a portion of the blades with some attendant reduction in friction loss.

The authors state that "the value of sigma at which efficiency and discharge were found to break, was taken as the cavitation limit." The true cavitation limit, however, is the point at which any one of the curves, quantity, power or efficiency, starts to break, or in other words, to be affected by cavitation.

It is to be hoped that at some time in the future cavitation tests will be made at Safe Harbor to determine the relation between the break in sigma on the large turbines with that on the model. This would, of course, require varying the tailwater and headwater levels, and a large number of runs under constant head with definite gate and blade positions. But on the other hand, the data obtained would be, it is believed, unique, and of great value.

**H. S. Van Patter:** The writer has read with interest the reasons for the selection of Kaplan turbines for the Safe Harbor Plant, and the description of the Holtwood Hydraulic Laboratory and of the tests conducted therein to determine the most suitable design of turbine casing and draft tube for the Safe Harbor units. The officials and engineers of the Pennsylvania Water and Power Company deserve much credit for undertaking the expense and labor involved in such research work.

From personal experience, the writer can appreciate the immense value of research work of this character. The Shawinigan Water and Power Company has had a similar testing plant in operation at Shawinigan Falls, Quebec, since 1924, and the writer has had the pleasure of working with the engineers of this company in connection with the tests conducted therein. To a considerable extent, these tests dealt with the phenomena of cavitation and pitting of propeller type turbines and determination of the most suitable designs for use under heads of 50 feet and higher. A considerable number of runners and various designs of guide vanes, throat rings, and draft tubes have been tested.

The testing procedure used in recent years has been quite similar to that outlined by Messrs. Davis and Spaulding, *i. e.*, by determining the power, efficiency and discharge at various gate openings for a range of sigma values. It was felt, however, that entire reliance should not be placed on this method only, as the proper interpretation of the results so obtained is, to a considerable extent, a matter of opinion without a mass of data on the correlation between model tests and field results. Consequently a technique has been developed for studying the actual effects of cavitation on the surfaces of the runner blades, throat ring and draft tube by the use of surface coatings which are unaffected under normal conditions of operation but which are readily removed by pitting action. Very good results have been obtained by using nickel plating on the bronze runner blades and two coats of different colored paint on the surrounding cast iron surfaces.

Why was it considered necessary to hold the total head constant when varying the suction head and has the decision in this respect been confirmed by test results? In other words, have the authors' tests shown that the cavitation point is affected by variations in total head?

The authors state that in determining the safe value of sigma, the value at which the efficiency and discharge curves break is taken as the limit. Referring to Fig. 6, for best gate opening 2.0 the efficiency curve breaks at sigma 1.25 and the discharge at 1.05. Is this variation characteristic? If so, which value is used?

The writer would like to point out that the comparison of unit spacing required for Francis and Kaplan turbines for the Safe Harbor units would not apply in the case of a base load plant where either type of unit would be operated normally at best efficiency point. In this case there would be little if any difference between the two types.

**F. H. Hollister:** (For discussion see page 188.)

**G. W. Spaulding and L. M. Davis:** Professor E. Brown raises several important questions. Fig. 6 refers to a test at normal speed but at maximum blade angle, consequently the model efficiency is rather low. The guaranteed efficiency for these conditions is only 80.5 per cent.

It is a peculiarity of the Safe Harbor turbine design that the break in the efficiency curve occurs at a higher value of sigma than the break in the unit quantity curve. Other models tested in the Holtwood laboratory show a sharper efficiency break and both unit quantity and efficiency breaking at the same values of sigma. The discrepancy in unit quantity and efficiency breaks caused considerable controversy before the decision was finally reached to use the break in the unit quantity curve. As a final check on this decision one unit was operated on power limits derived from the break in the efficiency curve for ten months and the progress of paint erosion compared with the other units operating at the higher power limits. As there was no noticeable difference in the rate or magnitude of paint erosion on this unit in comparison with the other units it was placed on the higher power limits. There is little doubt that cavitation occurs at higher sigma values than the break in the efficiency curve. However, unless it reduces the efficiency or attacks the metal parts it is not objectionable.

The draft head was measured from the center line of the runner.

It is known that, theoretically, the variation of the ratio of diameter of runner to head affects the critical value of sigma. Since the extent of this effect was uncertain the Holtwood laboratory was designed to permit constant head testing. After making tests in which the head was varied from 35 ft to 50 ft it was concluded that the effect on the cavitation limit, within the range of tests, was not apparent.

Mr. J. A. Peck's questions have been partially discussed in the preceding paragraphs. As he suggested the milky or cloudy condition of the water gradually increases over a wide range of sigma. The first cloudiness is visible at much higher values of sigma than the break in the efficiency curve.

At the time of the Safe Harbor model tests, there was some thought given to paint erosion tests on the throat ring and draft tube as mentioned by Messrs. L. B. Stirling, J. B. MacPhail and H. S. Van Patter. However, after the cavitation tests were completed it was noted that the shop coat of red lead was still in perfect condition on the model draft tube. This was taken as excellent evidence that no pitting would occur in the draft tube. The Safe Harbor units have been carefully inspected from time to time and after over a year's operation there is no indication of pitting on the throat ring or draft tube.

Mr. R. E. B. Sharp's observation of visual evidences of cavitation occurring along the trailing portion of the runner blades nearest the hub is correct. Since ordinarily the first trace of pitting on a propeller runner occurs on the bottom surface near the trailing edge and the periphery we were indeed surprised to note that the first visual evidences of cavitation occurred near the hub. The only explanation that has been advanced is the one suggested by Mr. Sharp, that cavitation is caused by the water not being able to close in smoothly after passing the thick fillet near the hub and the collapse of these cavities thus formed occurs below the runner in the draft tube, thus the blades near the hub are untouched.

# The Principle of Condenser Discharge
## Applied to Central Station Control Problems

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**Synopsis.**—*The paper describes the principle of a resistor coupled condenser discharge circuit as a means for indicating the rate of change of an electrical potential. The application of this circuit to an impulse relay which may be used in connection with quick response excitation regulating equipment is outlined.*

*The principle of operation of an electronic voltage regulator is referred to, and an oscillogram is given indicating the definite anti-hunting action which can be obtained with the condenser discharge circuit as an anti-hunting means.*

*A thermionic type automatic synchronizer, which requires only 5 voltamperes per potential transformer, is described in detail. The paper treats the method by which, for any frequency difference within limits of present operating practise, the synchronizer will cause the closing coil of the circuit breaker to be energized in advance of synchronism by a time equal to that required to close the breaker, so that, assuming the frequency difference between the two systems remains constant during the short time required to close the breaker, the breaker contacts will always be closed at the instant of zero voltage phase displacement.*

*A formula has been derived whereby the synchronizer "advance" may be calculated for various frequency differences when the constants of the thermionic circuits are known, and the results obtained with the thermionic type automatic synchronizer in a generating station with propeller type water wheels are described.*

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### INTRODUCTION

DURING the past few years the application of electronic tubes has been a topic of increasing interest to electrical engineers. Electronic devices are now rapidly supplanting electro-mechanical apparatus in a multiplicity of applications, and the versatile electronic tube is put to work in new control devices, performing duties which could not have been accomplished with the electro-mechanical devices previously available.

The combination of a condenser discharge circuit and an electronic tube provides the fundamental elements for indicating the rate of change and the direction of change of an electrical potential. The purpose of this paper is to outline the fundamental principle of the condenser discharge circuit, and to describe its application in connection with three specific electronic control devices, namely, an impulse relay, an electronic voltage regulator, and an automatic synchronizer.

### FUNDAMENTAL CONDENSER DISCHARGE CIRCUIT

The fundamental circuit consists of a condenser 1 connected in series with a resistor 2, which is connected in the grid circuit of tube 3, as shown in Fig. 1. The current through tube 3, for a definite plate voltage $E_P$ depends upon the voltage $E_g$ of the grid bias battery 4, and the characteristic curve for a tube will be as shown in Fig. 2. If a voltage $E_1$ is applied with a polarity as shown in Fig. 1 a charging current will flow through resistor 2 to the condenser. This charging current will produce a voltage drop across the resistor with a polarity as indicated in Fig. 1. Consequently the bias on the grid of tube 3 will become more positive and the current through tube 3 will increase. After a definite time, dependent upon the time constant $RC$ of the discharge circuit, the condenser will be fully charged, and the charging current, and consequently the voltage drop across the resistor will become zero, so that the current through tube 3 will come back to the original value as determined by the grid bias battery. If now voltage $E_1$ is varied we obtain a voltage drop across resistor 2 which is essentially proportional to the rate of change of $E_1$, and the polarity of this voltage drop will reverse if the direction of change of $E_1$ is reversed. The important features of this circuit are primarily that the current through tube 3 is not affected by the magnitude of voltage $E_1$, but is only affected by the rate of change of $E_1$, and further, that since resistor 2 may be several megohms, only a minute amount of control power is needed.

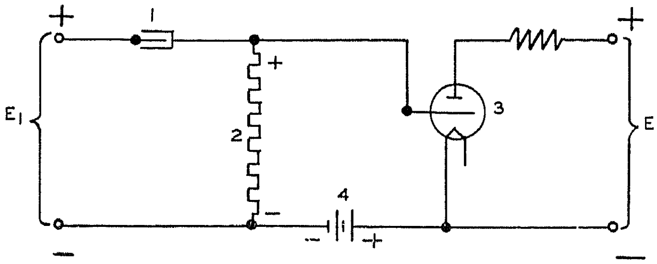

FIG. 1—FUNDAMENTAL CONDENSER DISCHARGE CIRCUIT

### IMPULSE RELAY

A possible application for the condenser discharge circuit is in connection with an impulse relay for quick response excitation voltage regulators. With this type of equipment it is highly desirable to provide additional field forcing by shunting out all resistance in series with the exciter fields, if a sudden drop in regulated voltage should occur. It is imperative that the quick response excitation element operates with a minimum time delay, and it is desirable to arrange the quick response element separate from the main control element so that separate adjustment may be obtained, and so that calibration of the main control element does not affect the adjustment of the quick response element.

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The various types of electro-mechanical voltage regulators for quick response excitation now on the market are equipped with an additional pair of contacts which will close if the regulated voltage drops for example 5 per cent below the normal value. It is obvious that the time between the drop in regulated voltage and the closure of the quick response contacts depends upon the position of the moving element of the regulator at the instant of voltage disturbance, so that the time interval will be increased if the regulator element were in the "lower" position, *i.e.*, the regulated voltage was slightly too high when the load disturbance occurred. By using an electronic type quick response element the response of the regulating equipment would be independent of the voltage conditions previous to the load disturbance, and would only depend upon the magnitude of the voltage drop.

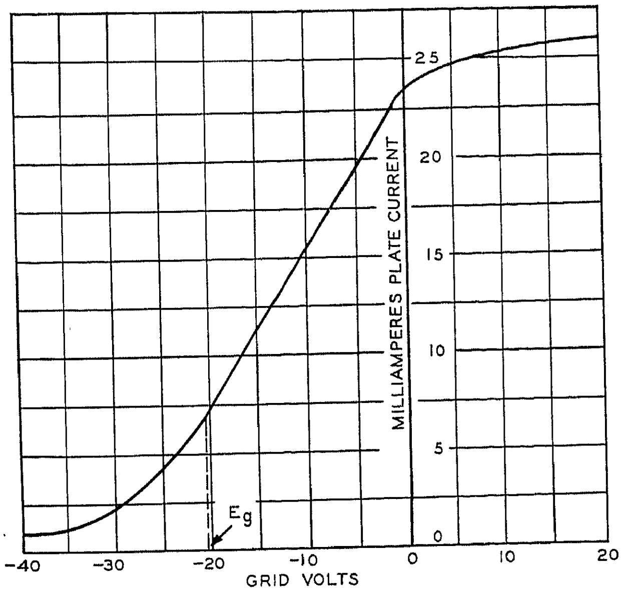

FIG. 2—TUBE CHARACTERISTIC

A schematic diagram of the impulse relay circuit is shown in Fig. 3. A transformer 1 is connected to the regulated voltage source and feeds into the full wave rectifier tube 2. The direct-current voltage across resistor 3 will, therefore, be proportional to the regulated voltage. An amplifier tube 4 is connected to resistor 3 in such a manner that the plate current of tube 4 does not change if the regulated voltage changes slowly. This is obtained by selecting the location of the resistor tap so that any change in tube plate voltage is compensated for by a proportional change in grid bias voltage. This condition is determined by the amplification constant of the tube. A resistor 5 and a condensor 6 are connected in a discharge circuit to the grid of tube 4 so that for decreasing regulated voltage the grid of tube 4 will become more negative and consequently the voltage drop across resistor 7 will decrease due to the decreased plate current of tube 4. When the voltage drop across resistor 7 decreases, a voltage drop will obtain across resistor 8 due to the discharging action of condenser 9. The polarity of the voltage drop across resistor 8 will be as indicated in the diagram, so that the grid voltage of the glow tube 10 becomes more positive and causes tube 10 to break down and energize the quick response shunting contactor coil 11. Contactor 11 remains closed until the direct-current supply voltage for tube 10 is disconnected by means of the contacts 13 of the field current limiting relay. The d-c supply for tube 10 is supplied from the 250 volts station bus through the voltage divider 12.

The response of this equipment compares favorably with the electro-mechanical quick response elements at their best and the response does not, as previously stated, depend upon the voltage conditions immediately before the fault occurred.

### ELECTRONIC VOLTAGE REGULATORS

The condenser discharge circuit is an important feature of electronic type voltage regulators which have recently been brought on the market. These regulators are now available for direct-current and alternating-current generator voltage regulation. The electronic regulator for d-c generators applies high vacuum tubes as power tubes and has a field current regulating range of 0.75 amp. The electronic voltage regulator for a-c generators applies glow tubes as power tubes and in its present design can handle a maximum field current of 8 amperes. The important features of these electronic type regulators are the high sensitivity of ± 0.2 per cent, the simplicity of operation, and the extremely fast response characteristic.

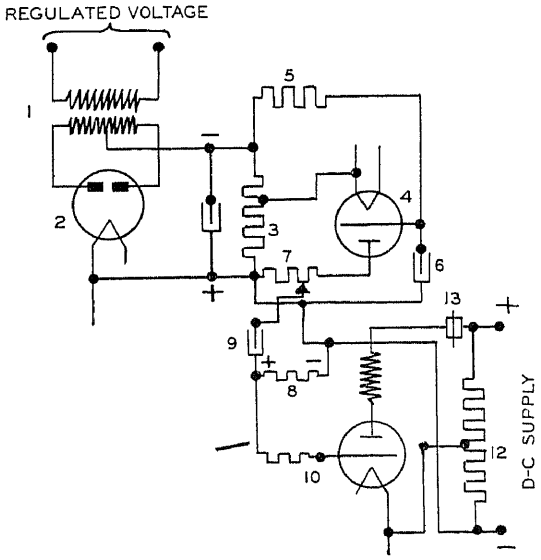

FIG. 3—IMPULSE RELAY

The fast response characteristic is made possible through the application of the condenser discharge circuit as an anti-hunting means.

Due to the inductive lag of the field windings of exciters and generators, the generator armature voltage will always be lagging in relation to the exciter field current, if the exciter field current is undergoing a change as a result of regulator action. If no anti-hunting means are supplied, the generator armature voltage will not have reached the normal value when the exciter field current attains the value corresponding to the new generator load conditions. Consequently, when the generator voltage is brought back to the normal value the exciter field current will be too high if the regulator action was caused by a drop in the regulated voltage, and even though the regulator immediately will start to decrease the exciter field current, the generator armature voltage will continue to increase for a definite time dependent upon the time lag characteristic of the machine combination. It is obvious that such a system will be unstable unless a zone is introduced within the limits of which the voltage being regulated can vary, without bringing into play the field current correcting forces, and it is apparent that the width of this zone of inaction must be increased if the speed of response of the regulating equipment is increased.

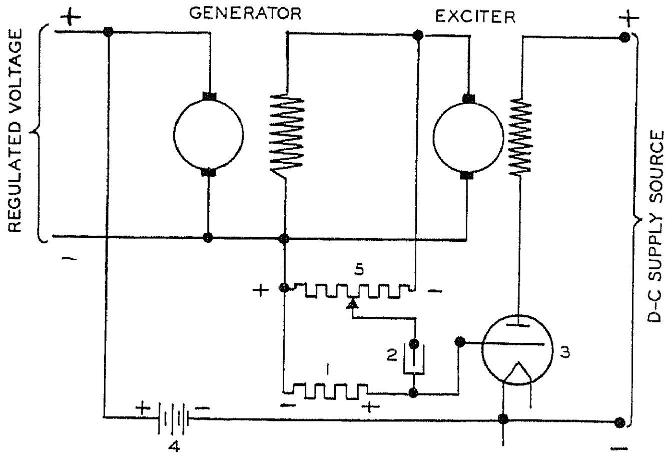

Fig. 4—Schematic Diagram of Electronic Voltage Regulator

To obtain quick response as well as high sensitivity with any regulating equipment it therefore becomes necessary to introduce corrective forces which will act upon the regulating element so that at all times the rate of generator voltage change is proportional to the error in regulated voltage.

A simplified schematic diagram of the electronic voltage regulator for d-c generators is shown in Fig. 4. The exciter field winding is connected in series with the electronic tube 3 which is supplied with plate voltage from a separate d-c source. The generator voltage is bucked by means of battery 4 so that increasing generator voltage will increase the negative bias on the grid of tube 3 and consequently decrease the exciter field current. The anti-hunting action is obtained through the condenser discharge circuit consisting of resistor 1 and condenser 2, which are connected in series across the exciter armature. The action of the anti-hunting circuit is such that when the exciter armature voltage is decreasing the polarity of the voltage drop across resistor 1 will be as indicated in the diagram, and will, therefore, provide a positive bias on the grid of tube 3. This positive bias counteracts the original negative bias resulting from the initial increase in regulated voltage, and consequently tends to stabilize the equipment. It should be noted that the amount of anti-hunting force is proportional to the rate of change of exciter armature voltage, and that consequently the anti-hunting force is zero until the exciter armature voltage starts to change. The anti-hunting connection, therefore, does not tend to decrease the initial response of field current change. The amount of anti-hunting action can easily be adjusted by means of a small radio type potentiometer 5 shown in the diagram.

In Fig. 5 is shown an oscillogram which plainly illustrates the quick response characteristic of the electronic regulator, and shows the action of the anti-hunting element. From the oscillogram it may be seen that the exciter field current starts to decrease before the regulated voltage has reached the normal value. This oscillogram was obtained as full load was connected to the 5-kw generator.

## The Thermionic Type Automatic Synchronizer

The principal advantages of the thermionic type synchronizer are: (1) the proportional advance feature which provides means for energizing the breaker closing coil at a point in advance of synchronism proportional to the frequency difference, and, (2) the low voltampere burden of 5 voltamperes per potential transformer. Considering the steadily increasing use of condenser bushing potential devices with capacity limited to from 15 to 20 voltamperes it would seem that there is a definite need for a low capacity automatic synchronizing device, and the thermionic type automatic synchronizer should therefore find wide application.

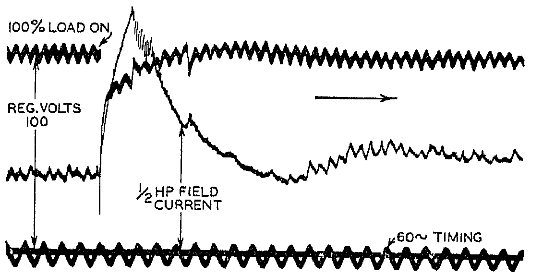

Fig. 5—Oscillogram of Regulator Response

The principle of operation of the thermionic synchronizer was described in a previous article,* and the reader is referred to this article for a complete description of the design and the operation of the equipment. In this paper, therefore, only a brief outline of the prin-

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*The *Electric Journal*, July 1931, pages 421-423.

ciple of operation is given, while the application of the condenser discharge principle to the proportional advance circuit is more thoroughly described.

The schematic diagram of the thermionic synchronizer is shown in Fig. 6. Two telephone type relays II and III are controlled by means of thermionic tubes so that relay III will operate at a fixed point in advance of synchronism, the closing characteristic being independent of the frequency difference; while relay II, the advance relay, will operate at a point in advance of synchronism proportional to the frequency difference. As shown in Fig. 6, an interlock is arranged between the two relays so that relay IV, which is energizing the breaker closing relay, is closed only if relay III is operated before relay II is closed.

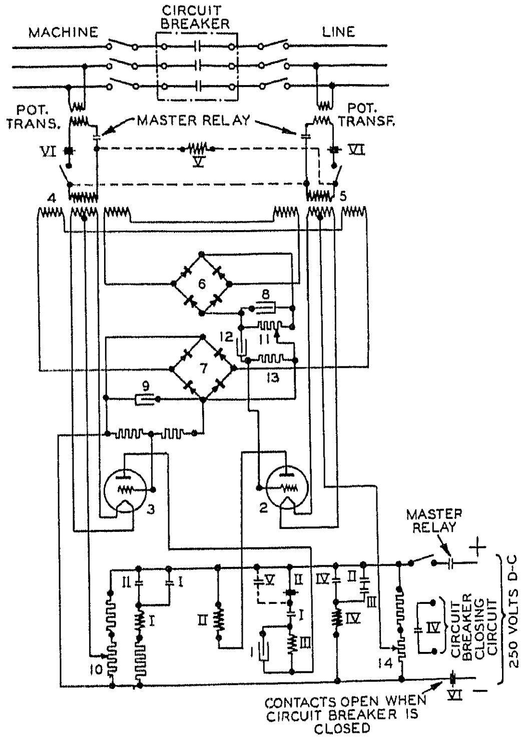

Fig. 6—Schematic Diagram of Thermionic Type Automatic Synchronizer

## Lock Out Relay III

A thermionic tube, indicated as 3 in Fig. 6 is connected in series with the coil of relay III across a 250-volt d-c supply circuit. The grid bias for tube 3 is supplied from the rectified beat voltage obtained from rectox 7. When the phase angle between the system voltages is 180 deg a high negative bias is, therefore, applied to the grid, and the tube current consequently is zero. When the phase angle is reduced, the negative bias is decreased and the current through relay III is increased. At a definite phase angle displacement between the system voltages the current through the coil of relay III will be high enough to operate the relay. By adjusting potentiometer 10 the operating point of relay III can be located at any position between zero deg and 40 deg phase angle displacement. The purpose of tube 3 and associated equipment is consequently only to provide definite closure of relay III at any predetermined phase angle displacement.

## Advance Feature

The proportional advance characteristic of relay II is obtained through the action of the condenser discharge circuit consisting of condenser 12, resistor 13 and rectox 6. The d-c output voltage of rectox 6 will be pulsating at a rate proportional to the frequency difference between the two systems to be paralleled. The voltage across the condenser 12 is equal to the output voltage of rectox 6, when the frequency difference is zero, and can be expressed by $e = E \cos \Phi$ where $E$ is the maximum voltage when the phase angle displacement $\alpha$ is 180 degrees and $\Phi$ is determined so that

$$\Phi = \frac{\pi}{2} \text{ when } \alpha = 0, \text{ and } \Phi = 0 \text{ when } \alpha = 180 = \pi.$$

The angle $\Phi$ may be expressed by $\Phi = \Delta f \pi t$ where $\Delta f$ is the frequency difference in cycles and $t$ is the time in seconds required for angle $\Phi$ to change from zero to $\Phi$. If there is a definite frequency difference $\Delta f$ between the two systems and the phase angle displacement $\alpha$ is changing from 180 deg towards zero, then the

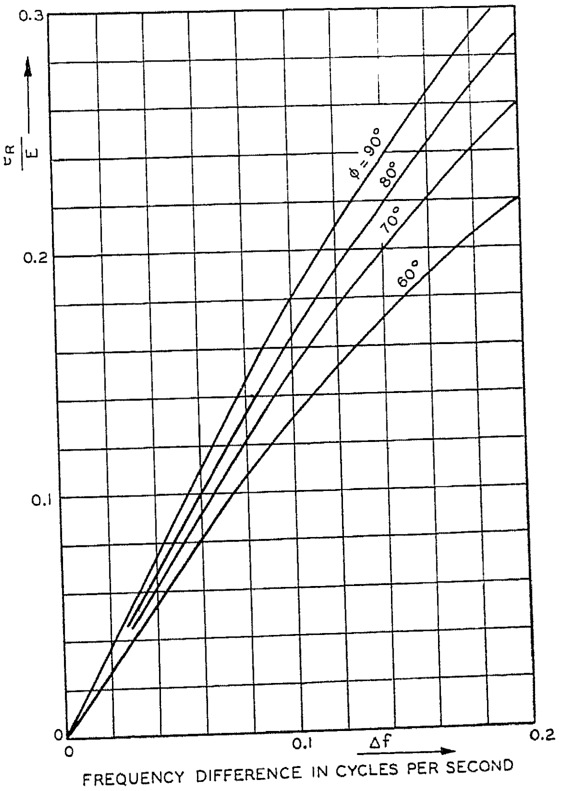

Fig. 7—Curves Showing Values of $\frac{e_R}{E}$ for Varying Frequency

Difference at various values of angle

voltage across the terminals of rectox 6 and the voltage across condenser 12 will be decreasing, but the voltage across condenser 12 will be higher than the rectox voltage by an amount dependent upon the time constant $RC$ of the discharge circuit and the frequency difference $\Delta f$. The discharge current from the condenser will produce a voltage drop across resistor 13 so that the potential on the grid of tube 2 will become less negative. When the phase angle displacement between the system voltages is increasing from zero to 180 deg the polarity of the voltage drop across the resistor will be reversed. Considering the performance of the automatic synchronizer the conditions for decreasing phase angle displacement only are of interest, since no relay action can take place when the phase angle displacement is increasing.

By using the nomenclature previously outlined the voltages in circuit 8-12-13 can be expressed by

$$e_c = E \cos \Phi - \Delta f RC\pi \frac{de_c}{d\Phi}$$

where $e_c$ is the condenser voltage. From this equation, as shown in the appendix, the ratio between the voltage drop across resistor $R$, and the maximum output voltage of rectox 6 is found to be

$$\frac{e_{\text{R}}}{E} = \frac{\Delta f RC\pi}{(\Delta f RC\pi)^2 + 1}$$

$$\left[ \Delta f RC\pi \cos\Phi - \sin\Phi - \Delta f RC\pi e^{\frac{-\Phi}{\Delta f RC\pi}} \right]$$

In Fig. 7 are shown curves giving $\frac{e_{\text{R}}}{E}$ for $RC = 0.58$ at different values of $\Phi$ for varying $\Delta f$. These curves show that the voltage drop across resistor 13 is substantially proportional to the frequency difference. It should be noted that the voltage ratio is calculated, assuming that the phase angle displacement is changing at a constant rate from $\alpha = 180$ degrees to $\alpha =$ zero. The curves give the voltage ratio at $\Phi = 60$; $\Phi = 70$; $\Phi = 80$ and $\Phi = 90$, corresponding to 60, 40, 20 deg and zero phase angle advance respectively.

In addition to the bias potential obtained from resistor 13, a constant negative bias is applied to the grid of tube 2 by means of potentiometer 14 and a varying negative bias is obtained from rectox 7. Potentiometer 14 is so adjusted that the negative grid bias obtained from the potentiometer is equal to $E_g$ in Fig. 2, corresponding to the operating current of relay II, consequently relay II will operate and close its contacts at zero phase angle displacement when the frequency difference is zero. For any definite frequency difference the closing point of relay II will correspond to that advanced phase angle position where the voltage given by the curves in Fig. 7 is equal to the voltage obtained from rectox 7.

In Fig. 8 are shown the curves from Fig. 7 and the voltage across rectox 7 plotted according to the same voltage scale. By means of these curves the frequency difference can be determined which will give relay closure at a definite advanced phase angle by drawing rectangle $b_1$—$b_2$—$b_3$—$b_4$. In order to determine the frequency difference at which relay II will close at a 40-deg phase angle, the line $b_1$—$b_2$ is located at 40 degrees advance. This gives rectox voltage $b_1$—$b_2$. As previously stated relay II will operate when the rectox voltage equals $e_{\text{R}}$. By drawing the horizontal line $b_2$—$b_3$ to its intersection with the curve for $e_{\text{R}}$ corresponding to the 40 deg advance position we obtain point $b_3$. The corresponding frequency difference 0.146 cycle is given by point $b_4$. The curves shown in Fig. 8 give the maximum value of $e_{\text{R}}$, and consequently give maximum advance, corresponding to approximately 27 deg per 0.1 cycle frequency difference. This would be suitable for a circuit breaker having 0.75 second closing time. In order to adjust the equipment to suit circuit breakers with shorter closing time the $e_{\text{R}}$ voltages are adjusted downwards by means of potentiometer 11 of Fig. 6. The calculated advance curve given in Fig. 9 shows how close the calculated data check with results obtained by actual tests.

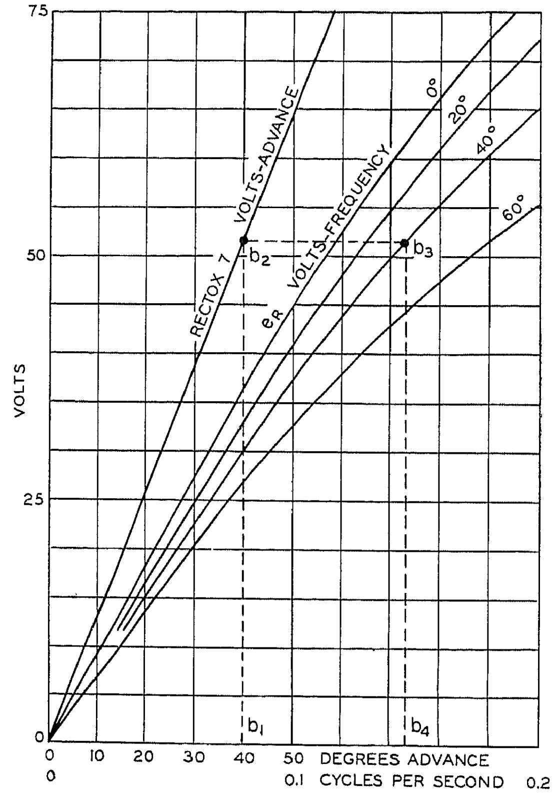

Fig. 8—Curves for Advance Calculation

## Voltage Error

For line voltage differences within 15 per cent of normal voltage the synchronizer operates practically without error so long as a definite frequency difference exists between the two sources to be connected. One reason for this is*, that the beat voltage at 30-deg phase angle displacement between the system voltages does not change appreciably, and the grid bias voltages of tubes 2 and 3 in Fig. 6, therefore, will remain unchanged. Furthermore a 15 per cent change in filament voltage does not affect the tube operation since the plate current is considerably below the maximum filament emission at rated voltage. When a voltage difference is present, there will be an equalizing current flowing between the two systems even if the breaker is closed at exactly zero phase angle displacement. This equalizing current will be proportional to the voltage difference at zero phase angle displacement, and will be proportional to the beat voltage at any other phase angle displacement. Since the beat voltage at 5-deg phase angle displacement is only 12 per cent higher than the beat voltage at zero phase angle displacement if a 15 per cent voltage difference is present, it will be realized that a few degrees error in synchronizer performance will have a negligible effect on the paralleling operation.

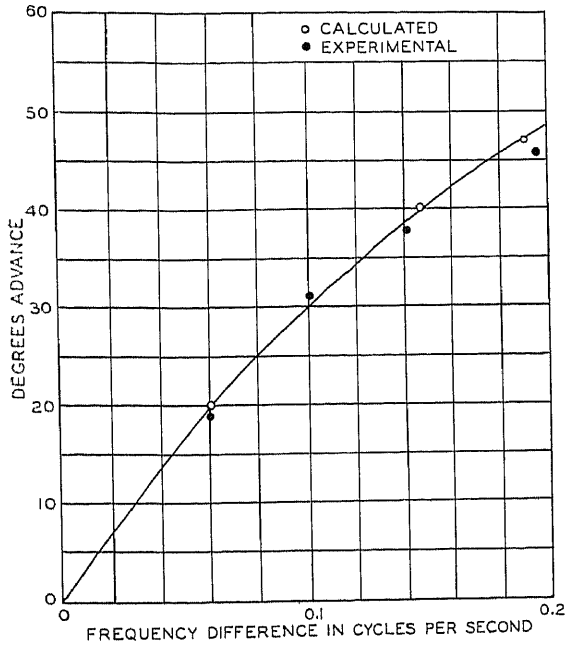

FIG. 9—CALCULATED CURVE FOR MAXIMUM ADVANCE. EXPERIMENTAL ADVANCE DATA

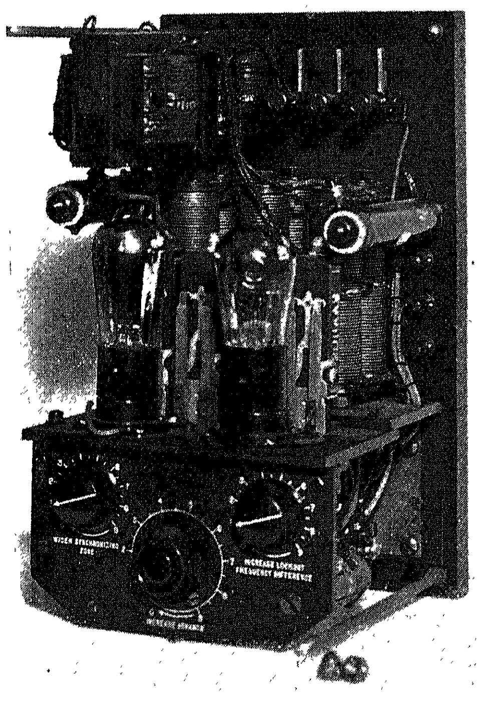

FIG. 10—THE THERMIONIC AUTOMATIC SYNCHRONIZER

In generating stations, synchronizing is usually accomplished at a frequency difference exceeding 1/10 cycle, and the phase angle error due to a 15 per cent voltage difference will under these conditions not exceed 4 degrees, which of course is quite satisfactory.

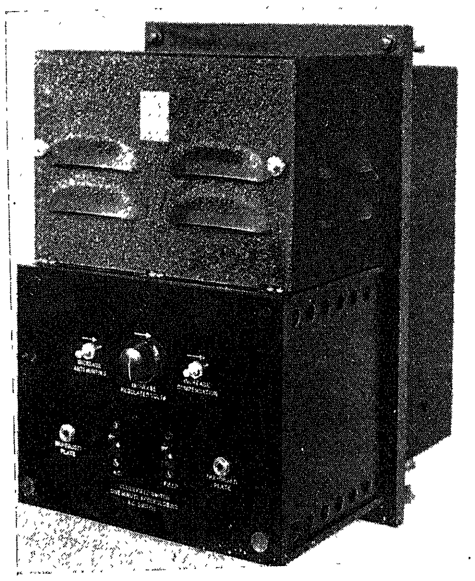

FIG. 11—THE ELECTRONIC VOLTAGE REGULATOR FOR DIRECT-CURRENT GENERATORS

When the synchronizer is applied to connect two systems the frequency difference will usually be below 1/10 cycle, and if the two systems are already tied together at some other point the frequency difference will be zero. To obtain breaker closure if a voltage difference is present under above conditions, it is necessary to widen the synchronizing zone. Recalibrated in this manner the synchronizer will perform perfectly at the maximum voltage difference for which the device was recalibrated; but will close too early if the voltage difference is zero. The amount of early closure measured in degrees will be equal to one-half of the maximum voltage difference in volts, referring to 110 volts as normal voltage.

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*See A.I.E.E. TRANS., Vol. 48, page 1185, Fig. 2.

### TUBE LIFE

The operating life of the thermionic tubes is in excess of 3,000 hours. Assuming that the synchronizer is in service during 1 hour each day, the useful life of the tubes would be approximately 8 years. It is apparent from Fig. 6 that in order to obtain breaker closure both relays II and III must operate. No faulty synchronizing can, therefore, take place due to tube failure.

### FIELD TESTS

Through the courtesy of the Kentucky Utilities Corporation a series of tests was made at the generating station located at Dam No. 7, Kentucky River. This station is equipped with three generators 850 kva, 150 rpm, driven by vertical propeller type waterwheels. Due to the low inertia of the units, and due to the inherent characteristic of the hydraulic equipment the frequency of these generators at no load is very erratic. The automatic switching equipment of the station is so arranged that any one of the three generating units could be started up either by means of push-button control in the station or by means of supervisory control. During the tests, as recorded in Table I, the time required for the various units to get up to synchronous speed was observed as well as the total synchronizing time from the start of a unit until breaker closure. In column 5 of Table I is given the time during which the synchronizer was in actual control, and the performance of the synchronizer should be judged by these data. It may be seen that the average synchronizing time for units Nos. 1, 2, and 3 respectively was 51 sec, 40 sec, and 60 sec, which must be considered highly satisfactory in a station of this type where the machine frequency is at least 50 per cent more erratic than in the average hydroelectric station. In column 6 is shown the phase angle displacement between the machine voltage and the system voltage at the instant of breaker closure; the maximum phase angle error being 15 degrees, and the average error 5 degrees.

TABLE I

| 1<br>Test No. | 2<br>Unit No. | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| 1 | 1 | 0.40 | 1.17 | 0.37 | 0 |
| 2 | 1 | 0.40 | 4.30 | 3.50 | 5 |
| 3 | 1 | 0.41 | 1.03 | 0.22 | 5 |
| 4 | 1 | 0.39 | 5.07 | 4.28 | 15 |
| 5 | 1 | 0.41 | 1.14 | 0.33 | 0 |
| 6 | 1 | 0.40 | 1.07 | 0.27 | 0 |
| 7 | 1 | 0.39 | 0.47 | 0.08 | 10 |
| 8 | 1 | 0.38 | 1.04 | 0.26 | 5 |
| 9 | 1 | 0.40 | 0.59 | 0.19 | 5 |
| 10 | 1 | 0.39 | 1.09 | 0.30 | 0 |
| 11 | 1 | 0.39 | 0.51 | 0.12 | 5 |
| 12 | 1 | 0.39 | 0.46 | 0.07 | 0 |
| 13 | 1 | 0.39 | 1.51 | 1.12 | 10 |
| 14 | 1 | 0.37 | 0.51 | 0.14 | 5 |
| 15 | 1 | 0.40 | 0.49 | 0.09 | 0 |
| 16 | 1 | 0.38 | 1.51 | 0.13 | 5 |
| 17 | 2 | 1.00 | 1.34 | 0.34 | 5 |
| 18 | 2 | 0.57 | 2.10 | 1.13 | 0 |
| 19 | 2 | 0.57 | 1.04 | 0.07 | 10 |
| 20 | 2 | 0.55 | 1.03 | 0.08 | 5 |
| 21 | 2 | 0.58 | 1.17 | 0.19 | 10 |
| 22 | 2 | 0.54 | 1.13 | 0.19 | 5 |
| 23 | 2 | 0.59 | 3.47 | 2.48 | 0 |
| 24 | 2 | 0.57 | 1.02 | 0.05 | 0 |
| 25 | 2 | 0.57 | 1.10 | 0.13 | 15 |
| 26 | 2 | 0.58 | 3.31 | 2.33 | 10 |
| 27 | 3 | 0.57 | 2.34 | 1.37 | 0 |
| 28 | 3 | 1.00 | 1.40 | 0.40 | 0 |
| 29 | 3 | 1.02 | 1.15 | 0.13 | 5 |
| 30 | 3 | 0.59 | 1.59 | 1.00 | 0 |
| 31 | 3 | 1.02 | 1.59 | 0.57 | 0 |
| 32 | 3 | 0.50 | 1.18 | 0.28 | 5 |
| 33 | 3 | 1.01 | 2.20 | 1.19 | 5 |
| 34 | 3 | 1.03 | 3.48 | 2.45 | 10 |
| 35 | 3 | 1.02 | 1.46 | 0.44 | 10 |

3 = Time in min. and seconds required for unit to come up to speed.
4 = Total synchronizing time from start of unit until breaker closure.
5 = Time during which synchronizer was connected.
6 = Degrees phase displacement at moment of breaker closure.

### CONCLUSION

The possibilities of useful application of the condenser discharge principle are numerous, and it is felt that the condenser discharge circuit will play an important role in the future development of electronic equipment for central station control.

## Appendix

Fundamental equation:

$$e_c = E\cos\Phi - \Delta f RC\pi \frac{de_c}{d\Phi} \qquad (1)$$

Introducing

$$\begin{cases} e_c = uv; \dfrac{de_c}{d\Phi} = u\dfrac{de_c}{d\Phi} + v\dfrac{du}{d\Phi} \\ G = \Delta f\pi RC \end{cases}$$

Gives:

$$uv = E\cos\Phi - G\left[u\frac{de_c}{d\Phi} + v\frac{du}{d\Phi}\right]$$

From this equation is found:

$$u = e^{\frac{-\Phi}{G}}$$

$$v = \frac{E}{G\left(1+\frac{1}{G^2}\right)} e^{\frac{\Phi}{G}}\left[\frac{\cos\Phi}{G} + \sin\Phi\right] + C_1$$

Consequently:

$$e_c = uv = c_1 e^{\frac{-\Phi}{G}} + \frac{E}{G\left(1+\frac{1}{G^2}\right)}\left[\frac{\cos\Phi}{G} + \sin\Phi\right] \qquad (2)$$

constant $c_1$ to be determined so that $e_c = E$ when $\Phi = 0$

which gives $C_1 = \dfrac{EG^2}{G^2+1}$

Substituting $c_1$ in equation (2) gives

$$e_c = \frac{EG^2}{G^2+1} e^{\frac{-\Phi}{G}} + \frac{E}{G\left(1+\frac{1}{G^2}\right)}\left[\frac{\cos\Phi}{G} + \sin\Phi\right]$$

From equation (1) is obtained since

$$e_R = \Delta fRC\pi \frac{de_c}{d\Phi}$$

$$\frac{e_R}{E} = \cos\Phi - \frac{e_c}{E}$$

$$\frac{e_R}{E} = \cos\Phi - \frac{G^2}{G^2+1}e^{\frac{-\Phi}{G}} - \frac{G}{G^2+1}\left[\frac{\cos\Phi}{G} + \sin\Phi\right]$$

$$= \frac{G}{G^2+1}\left[G\cos\Phi - \sin\Phi - Ge^{\frac{-\Phi}{G}}\right]$$

Substituting $G = \Delta fRC\pi$ gives final equation

$$\frac{e_R}{E} = \frac{\Delta fRC\pi}{(\Delta fRC\pi)^2+1}\left[\Delta fRC\pi\cos\Phi - \sin\Phi - \Delta fRC\pi\, e^{\frac{-\Phi}{G}}\right] \qquad (3)$$

This equation may be used in calculating the advance curves as shown in the main body of the paper.

# Direct Selection System of Supervisory Control

BY M. E. REAGAN*

Member, A.I.E.E.

MODERN supervisory control systems were designed and placed in permanent operation first approximately eleven years ago; they were of the "code" type and operated over three wires. In 1924, the "synchronous" systems were introduced. Recently, a demand for higher speed led to the development of a "direct selection" system which eliminates sequence stepping or counting chains. All systems operate over line wires of telephone size. Modern arrangements use two or four wires depending on the number of operations to be performed.

In order to obain an idea of the three general principles involved, first imagine a row of small control switches and associated indicating lamps in a dispatcher's office and a corresponding row of power switches or circuit breaker in some remote substation. Regardless of the number of operations to be performed, only two or four line wires are available first to select the proper switch and then to operate it, meanwhile obtaining a lamp indication of its open or closed position.

Synchronous selecting systems shift both ends of the line wires simultaneously from point to point. Thus, the lines are connected first to No. 1 control switch in the office and No. 1 switch in the substation; then they are disconnected concurrently at both ends and reconnected to No. 2 control switch in the office and No. 2 circuit breaker in the distant substation. This action is repeated until the wires reach the breaker to be operated. Here the stepping action ceases and the line wires are used for direct control. The breaker may be opened or closed at the will of the dispatcher and corresponding lamp signals give him the indication of its position. Thus it may be seen that some time is consumed by connecting the line wires to breakers on which no operation is wanted. Such stepping means usually operate at approximately ten steps per second so that 5 seconds' time would be required to reach the 50th breaker before any operation could be accomplished.

Code selecting systems operate on a different principle. The plan of selection of one type is first to switch the substation end of the line wire circuits from breaker to breaker until the desired one is reached, by a definite number of impulses sent from the dispatcher's office. The substation equipment then sends an equal number of checking impulses to the office to step that end of the line wire circuits from control switch to control switch until the corresponding one is attained. Again, the breaker may be opened and closed as desired by the dispatcher and at the same time he gets a lamp indication of its status. Here, also, some time is consumed in the selection. In the two-wire all-relay type, the total selecting time is approximately double that taken by the synchronous system since the check-back takes as long as the selection.

Direct selection systems are practically instantaneous inasmuch as the mode of operation consists of sending a single direct-acting impulse from a control switch at the dispatching office direct to the related circuit breaker at the substation. Instead of switching the line wires by stepping them from point to point, they are connected instantly to the control switch and corresponding circuit breaker by means of circuits which can receive only electric currents having definite combinations of polarities. Each breaker, therefore, has a definite combination to which it alone responds so that a single impulse of the proper combination immediately selects that particular breaker. No time is required or consumed in connecting the line wires to points where they are not to be used. To insure the accuracy of the selection, however, a checking impulse is returned from the breaker to the dispatcher's office. The time of choosing the breaker and obtaining the verification of its correctness is the same for each breaker.

The control equipment in the dispatcher's office for each circuit breaker is the same as used on practically all previous supervisory systems and consists of:

1 point selection lamp which indicates that the proper point has been selected before operation is attempted.

1 disagreement lamp which indicates an automatic operation in the substation.

1 "trip" supervisory lamp which lights when device is open.

1 "close" supervisory lamp which lights when device is closed.

1 control key whose position determines the operation of "close" or "trip."

1 point selection button which connects the selecting combinations of polarities to the line wires.

There is also common equipment consisting of:

1 operation control button which sends the "close" or "trip" operating impulse to the substation.

1 release button for resetting equipment and stopping an alarm.

Besides the relay equipment and that just listed, the control office is equipped with one 48-volt storage battery, charging facilities, and line wire protectors. The substation equipment consists of corresponding relay equipment, interposing relays, one 48-volt storage battery, charging facilities, and line wire protectors.

The direct-selection system is based upon the fundamental method of relay valve operation in which current through the relay in one direction operates it and current is blocked from the relay in the other direction. In the four-wire classification, the pushbutton in the dispatcher's office functions to connect battery polarities

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*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., Jan. 23-27, 1933.*

to the line wires and to operate the register relays at the substation. The receiving relay group consists of eight unidirectional relay circuits; for these, ordinary neutral relays with copper oxide rectifier valves are employed in order that time-proved devices may be utilized in a manner such that they perform their usual functions.

The four-wire system is based also upon the employment of individual point selection relays at both ends of the line wires. These relays are particularly useful at the substation to prevent interference between supervisory indications originated at the same instant by the simultaneous tripping of several circuit breakers. Furthermore, they assure the dispatcher that the desired breaker has been selected and connected to the line wires before he attempts operation.

Briefly, an operation is performed by first pressing the point-selection button and waiting until the point-selection lamp glows, indicating that the desired equipment is connected to the line wires ready to be operated; this requires about 0.4 sec. The control key then is turned to the desired operation (in the case of breakers, "close" or "trip") after which pressing the operation control key causes the substation equipment to change position; an indication of the new position then comes to the dispatcher automatically.

To give a more detailed account of this procedure a short outline of the circuit functions is given. In the normal condition of the line circuit both ends are held in readiness for operation over a circuit through the line wires and relays at each end in series. As soon as an operation is initiated from the dispatcher's end or a supervisory indication originated from the substation, this normal circuit is opened in order to disconnect the starting relay at the end which is to act as the receiving end in the succeeding function. By this means interference is prevented effectively when both ends attempt to initiate a selection at the same time.

Assuming that the dispatcher originates the selection, a single impulse is transmitted from the office to the substation after the normal circuit has been opened. A different combination of positive and negative battery potential is applied to the four-line wires for each of 50 points, thereby energizing the selection relay of the desired point at the substation, through intermediate receiving relays.

When the point selection relay at the substation is energized, it sends a second single impulse back to the dispatcher's office where this impulse causes the operation of the proper point selecting relay. The polarity combination of the return impulse is different from that of the first impulse in order to provide double assurance that the proper relay has been selected at the substation. Simultaneously with the operation of the point-selection relay at the office, the associated point-selection lamp is caused to glow, thus informing the dispatcher that the selection is completed.

If, by reason of induced currents from adjacent power line disturbances, a point-selection relay other than the desired one has been selected at the substation, a polarity combination will be returned to the office which will cause the glowing of a point-selection lamp not associated with the originating point. Also, if for the same reason the correct point-selection relay has been operated at the substation, but the return impulse fails to energize the correct point-selection relay at the office, the point-selection lamp of the originating point will not glow, but that of another point. Therefore, if the dispatcher sees the point-selection lamp of the selected point glow, he is assured that the established connection is correct; if he doesn't, he resets and reselects.

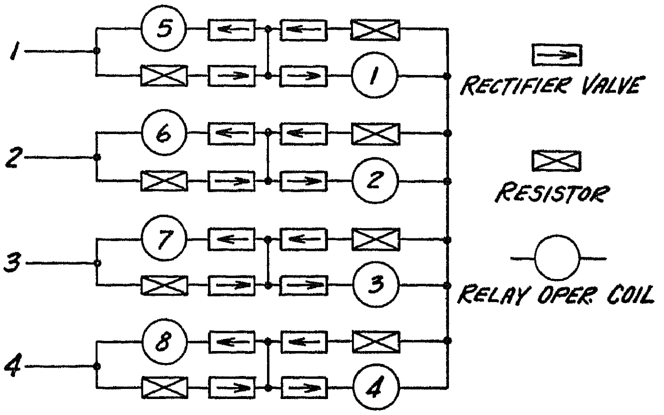

Fig. 1—Schematic Diagram of Receiving Relay Circuits for a Four-Wire System

The point-selection relays remain energized and two of the line wires are connected through to the individual point equipment for control and supervision, while the remaining two line wires are utilized to maintain the connection until the selection key is restored to its original position. An alarm may be provided to insure the release of the equipment by the dispatcher.

If an automatic operation occurring at the substation is to transmit the corresponding supervisory indication to the office, a single impulse is sent to the office, causing the operation of the corresponding point-selection relay. The operation of the office relay sends a checking impulse to the associated point-selection relay at the substation. The control and supervisory line wires then are connected through and the supervisory indication transmitted to the office. The connection is maintained until the supervisory lamps at the office actually have changed to agree with the new position of the supervised device, whereupon the connection is released automatically and the circuit returns to its normal rest condition.

Means are provided at the substation for effecting a proper succession of supervisory signals, if two or more supervised devices at the substation change their positions at the same time. This guarding arrangement is effective even if several devices change their positions at exactly the same instant. This is accomplished by interlocked relay circuits in which only one relay may be operated at a time.

Brief intervals are introduced between the normal rest condition and the first impulse, between this first impulse and the return impulse and between the return impulse and the completion of the control and supervisory connections, during which intervals the line wires are disconnected entirely at both ends. The purpose of these intervals is to give each end sufficient time for the preparation of the next succeeding function.

Potential from the 48-volt battery is applied to the four-line wires according to the 50 polarity combinations shown in Table I. Code No. 1 calls for positive potential on line 1 and negative potentials on line 2 with lines 3 and 4 remaining open (not used); relays 1 and 6 respond as may be seen from Fig. 1. Again code No. 50 calls for positive potential on line 1 and negative potential on lines 2, 3, and 4; relays 1, 6, 7, and 8 respond. Thus each selection puts some code of polarities on the line wires; hence the name "Polaricode" has been applied. Two-line wires only are used for twelve of the 50 codes; three only are used for 24 codes, while all four are used on the remaining fourteen codes.

A diagram of the receiving relays with their associated register circuit is shown in Fig. 2. As already mentioned, the selection of No. 1 breaker calls for the energizing of relays 1 and 6; at the substation end, these are known as S1 and S6. When the contacts of S1 and S6 are closed, relays S11 and S16 are energized. Relay S11 in turn energizes relay S26 over "break" contacts of relays S12, S13, and S14. This completes the selection circuit for register relay No. 1 from battery positive through "break" contacts of S15, "make" contacts of S16, "break" contacts of S17 and S18, "make" contact of S26, and No. 1 relay coil to negative battery. The other register relays are energized by similar apparatus circuits. Thus any one of fifty breakers can be selected by a single impulse over four-line wires. The time for any one of the fifty selections, including check-back, is approximately 0.4 sec.

TABLE I—POLARITY COMBINATIONS

| Code No. | Lines 1 | Lines 2 | Lines 3 | Lines 4 | Relays 1 | Relays 2 | Relays 3 | Relays 4 | Relays 5 | Relays 6 | Relays 7 | Relays 8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | + | − | | | 1 | ... | ... | ... | ... | 6 | ... | ... |
| 2 | + | | − | | 1 | ... | ... | ... | ... | ... | 7 | ... |
| 3 | + | | | − | 1 | ... | ... | ... | ... | ... | ... | 8 |
| 4 | | + | − | | ... | 2 | ... | ... | ... | ... | 7 | ... |
| 5 | | + | | − | ... | 2 | ... | ... | ... | ... | ... | 8 |
| 6 | | | + | − | ... | ... | 3 | ... | ... | ... | ... | 8 |
| 7 | + | + | − | | 1 | 2 | ... | ... | ... | ... | 7 | ... |
| 8 | + | + | | − | 1 | 2 | ... | ... | ... | ... | ... | 8 |
| 9 | + | | + | − | 1 | ... | 3 | ... | ... | ... | ... | 8 |
| 10 | | + | + | − | ... | 2 | 3 | ... | ... | ... | ... | 8 |
| 11 | + | − | + | | 1 | ... | 3 | ... | ... | 6 | ... | ... |
| 12 | + | − | | + | 1 | ... | ... | 4 | ... | 6 | ... | ... |
| 13 | + | | − | + | 1 | ... | ... | 4 | ... | ... | 7 | ... |
| 14 | | + | − | + | ... | 2 | ... | 4 | ... | ... | 7 | ... |
| 15 | − | + | + | | ... | 2 | 3 | ... | 5 | ... | ... | ... |
| 16 | − | + | | + | ... | 2 | ... | 4 | 5 | ... | ... | ... |
| 17 | − | | + | + | ... | ... | 3 | 4 | 5 | ... | ... | ... |
| 18 | | − | + | + | ... | ... | 3 | 4 | ... | 6 | ... | ... |
| 19 | + | + | − | − | 1 | 2 | ... | ... | ... | ... | 7 | 8 |
| 20 | + | − | + | − | 1 | ... | 3 | ... | ... | 6 | ... | 8 |
| 21 | + | − | − | + | 1 | ... | ... | 4 | ... | 6 | 7 | ... |
| 22 | + | + | + | − | 1 | 2 | 3 | ... | ... | ... | ... | 8 |
| 23 | + | + | − | + | 1 | 2 | ... | 4 | ... | ... | 7 | ... |
| 24 | + | − | + | + | 1 | ... | 3 | 4 | ... | 6 | ... | ... |
| 25 | − | + | + | + | ... | 2 | 3 | 4 | 5 | ... | ... | ... |
| 26 | − | + | | | ... | 2 | ... | ... | 5 | ... | ... | ... |
| 27 | − | | + | | ... | ... | 3 | ... | 5 | ... | ... | ... |
| 28 | − | | | + | ... | ... | ... | 4 | 5 | ... | ... | ... |
| 29 | | − | + | | ... | ... | 3 | ... | ... | 6 | ... | ... |
| 30 | | − | | + | ... | ... | ... | 4 | ... | 6 | ... | ... |
| 31 | | | − | + | ... | ... | ... | 4 | ... | ... | 7 | ... |
| 32 | − | − | + | | ... | ... | 3 | ... | 5 | 6 | ... | ... |
| 33 | − | − | | + | ... | ... | ... | 4 | 5 | 6 | ... | ... |
| 34 | − | | − | + | ... | ... | ... | 4 | 5 | ... | 7 | ... |
| 35 | | − | − | + | ... | ... | ... | 4 | ... | 6 | 7 | ... |
| 36 | − | + | − | | ... | 2 | ... | ... | 5 | ... | 7 | ... |
| 37 | − | + | | − | ... | 2 | ... | ... | 5 | ... | ... | 8 |
| 38 | − | | + | − | ... | ... | 3 | ... | 5 | ... | ... | 8 |
| 39 | | − | + | − | ... | ... | 3 | ... | ... | 6 | ... | 8 |
| 40 | + | − | − | | 1 | ... | ... | ... | ... | 6 | 7 | ... |
| 41 | + | − | | − | 1 | ... | ... | ... | ... | 6 | ... | 8 |
| 42 | + | | − | − | 1 | ... | ... | ... | ... | ... | 7 | 8 |
| 43 | | + | − | − | ... | 2 | ... | ... | ... | ... | 7 | 8 |
| 44 | − | − | + | + | ... | ... | 3 | 4 | 5 | 6 | ... | ... |
| 45 | − | + | − | + | ... | 2 | ... | 4 | 5 | ... | 7 | ... |
| 46 | − | + | + | − | ... | 2 | 3 | ... | 5 | ... | ... | 8 |
| 47 | − | − | − | + | ... | ... | ... | 4 | 5 | 6 | 7 | ... |
| 48 | − | − | + | − | ... | ... | 3 | ... | 5 | 6 | ... | 8 |
| 49 | − | + | − | − | ... | 2 | ... | ... | 5 | ... | 7 | 8 |
| 50 | + | − | − | − | 1 | ... | ... | ... | ... | 6 | 7 | 8 |

Relays 1, 2, 3, and 4 operate when *positive* polarity is applied to lines 1, 2, 3, and 4, respectively; relays 5, 6, 7, and 8 operate when *negative* polarity applied to lines 1, 2, 3, and 4, respectively.

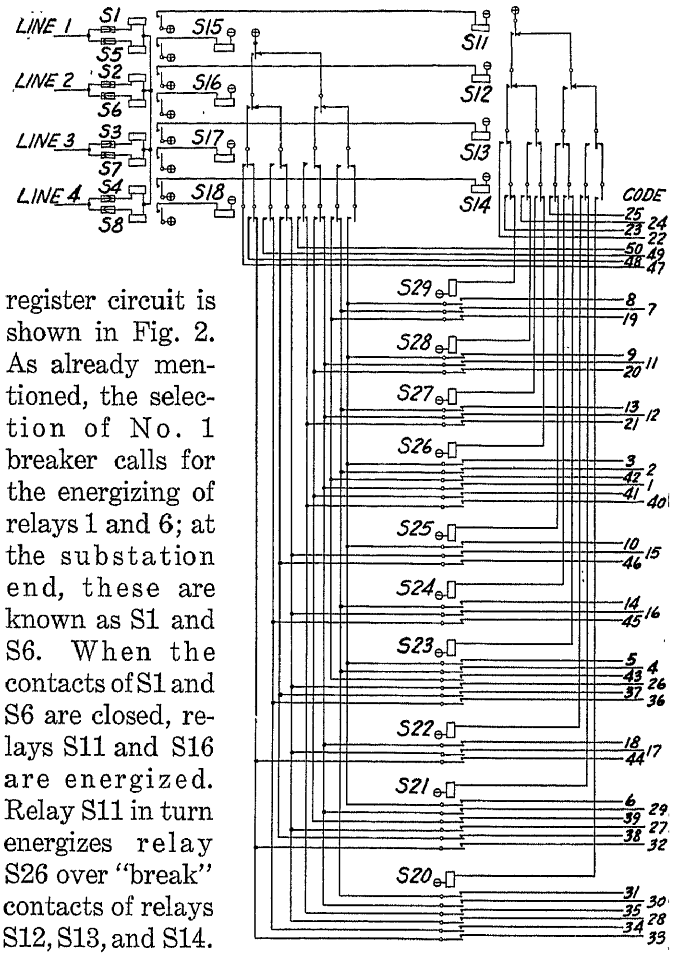

FIG. 2—REGISTER CIRCUIT OF FOUR-WIRE SYSTEM

The two-wire direct selection system utilizes pulsating battery voltage in addition to the direct voltage as utilized in the four-wire arrangement. If direct voltage alone were used, only two selections would be possible over two wires; the addition of the pulsating voltage provides for three more selections or a total of five. Thus on two wires the instantaneous selection of any one of five points is possible.

Referring to Fig. 3, the vibrating relay for producing the pulsating direct current is shown as relay *V*. Just to the right is the push-button arrangement for applying the five different potential combinations to the line wires. On the extreme right are the receiving relays in the substation. The contacts of the receiving relays determine which register relay responds.

The fundamental action in the two-wire polarized selection is as follows: Suppose both contacts of push-

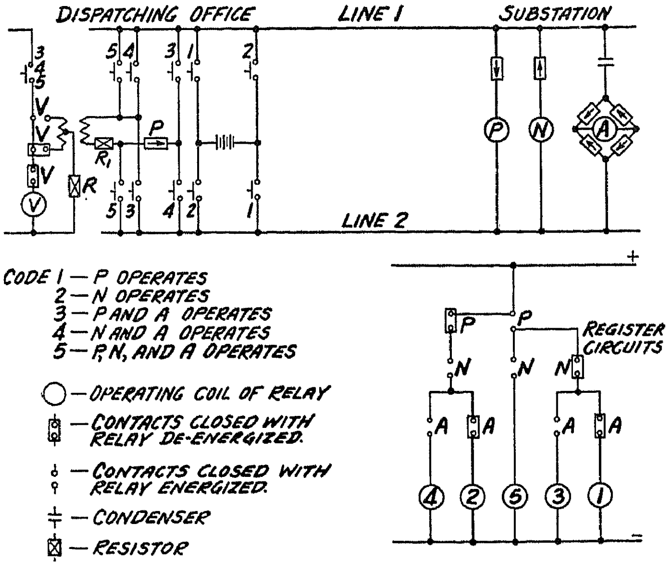

Fig. 3—Schematic Diagram of Two-Wire System

button 1 are closed. Positive battery is applied to the upper line wire and negative to the lower; relay *P* is energized. Relay *N* is not affected because of the rectifier valve in series with its operating coil; relay *A* is not affected because of the condenser. However, if the two contacts of pushbutton 2 are closed, the polarities of the line wires are reversed and relay *N* responds while relays *P* and *A* are unaffected.

Thus, when pushbutton 1 is closed, the circuit may be traced from positive battery, through "make" contacts of relay *P*, "break" contacts of relay *N*, "break" contacts of relay *A*, and the operating coil of relay 1 to battery negative. Thus relay 1 is energized almost instantly after pushbutton is operated. A similar circuit may be traced to energize relay 2 when pushbutton 2 is operated.

When any one of pushbuttons 3, 4, or 5 is pressed, the vibrating pole changer is started, producing pulsating voltage on the secondary of the transformer. This circuit may be traced from positive battery through the contacts of pushbuttons 3, 4, or 5, through two parallel paths to battery negative. The first of these paths goes through the "break" contacts of the vibrator *V*, through the operating coil of *V* to battery negative; the second path goes through another pair of "break" contacts of vibrator *V*, through half of the primary winding (in the up direction) of the transformer through resistor *R* to battery negative. Through the first path coil *V* is energized; this changes the position of its three sets of contacts so that a circuit is completed from battery positive through pushbuttons 3, 4, or 5, through "make" contacts on *V*, and through the other half of the transformer primary winding (in the down direction) and resistor *R* to battery negative.

As the coil *V* is energized, it is apparent that the break contact *V* in series with the operating coil is opened, which, in turn, deenergizes it. Thus the coil is alternately energized and deenergized rapidly. When deenergized, a half wave is produced in the transformer secondary in one direction and the energized position of *V* produces the other half wave in the opposite direction. The relay now in use produces about 70 cycles per second. The three combinations obtained from this source are full wave pulsating currents, positive pulsating (positive half wave) and negative pulsating (negative half wave), the latter two being obtained by rectifier *P*.

If pushbutton 3 is pressed, the positive half wave is impressed on the line wires. The circuit may be traced from the lower end of the transformer secondary winding, through resistor $R_1$, through rectifier *P*, through pushbutton contact 3, over line wire 1, through the relay circuits of *P* and *A* in parallel, over line wire 2, through another contact of pushbutton 3, to the other end of the secondary winding of the transformer. The substation selection circuit may be traced from battery positive, through "make" contact of relay *P*, through "break" contacts of relay *N*, through "make" contacts of relay *A*, through the operating coil of relay 3 to battery negative. Therefore, when pushbutton 3 is operated in the dispatching office, relay 3 in the substation responds.

The action of pushbutton 4 is similar to that of 3, except that the negative half wave is used. Relays *N* and *A* respond, which produces a register circuit such that relay 4 responds instantly. When pushbutton 5 is pressed, both half waves are impressed on the line wires so that the three relays *P*, *N*, and *A* respond and relay 5 is energized.

Since only five selections are available on two wires without going to other apparatus to obtain various voltage or frequencies, the simple way of expanding control is to send more than one selecting combination. With two combinations, any one of 25 can be selected.

Referring to Fig. 4, the first selecting impulse chooses one of the five paths labeled *A*, *B*, *C*, *D*, and *E*. Thus the circuit is completed from positive battery to one of the five groups. After this selection is checked back to the office, the second selecting impulse completes the circuit to the desired relay by energizing one of the relays in the group. If relay No. 17 is to be selected, the first selection would be the fourth code closing contact *D* and the second impulse would be the second code closing contacts *b*. One operation only is required by the dispatcher for selecting any one of the 25 relays.

In conclusion, the systems described are designed so that they may accommodate all of the auxiliaries used with other previously used assemblies. These include telemetering, remote synchronizing, and position control. The "anti-pumping" feature also is preserved.

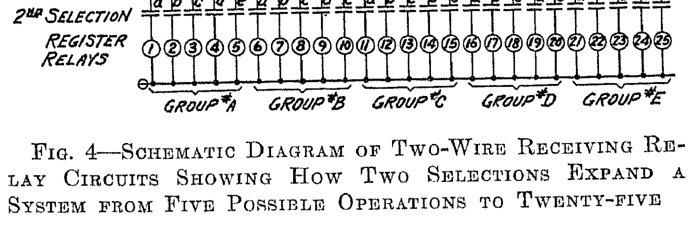

Fig. 4—Schematic Diagram of Two-Wire Receiving Relay Circuits Showing How Two Selections Expand a System from Five Possible Operations to Twenty-five

## Discussion

**S. S. Watkins:** What are the ways and means of eliminating inductive effect in the line wires and also is it possible to spread out the receiving equipment instead of having all of the substation apparatus located in one area?

**M. E. Reagan:** The two-wire system is very easily drained so that inductive interference will not in any way affect operation and the draining of the four-wire system is similar to present four-wire systems in that the receiving relays had to be bypassed by resonant shunt circuits. As far as the spreading out of the receiving equipment is concerned, all of the apparatus to be controlled should be in the same approximate location as the receiving apparatus. Some direct wire stations may be run for considerable distances where they are not subject to inductive interference.

**A. E. Anderson:** Asked about the speed of selection on the new systems.

**M. E. Reagan:** On the two-wire system it is possible to select and check any one of 5 in approximately 0.4 second and any one of 25 in approximately 0.8 second. On the four-wire system it is possible to select and check any one of 50 pieces of apparatus in 0.4 second and any one of 2,500 pieces in 0.8 second.

**D. W. Taylor:** What is the distance limitation and how were the number of operations increased?

**M. E. Reagan:** On this, the two- and four-wire direct selection system may not operate over quite the distances of previous systems since three relays are picked up over the line in the case of the two wire and as high as four relays over the line in the case of the four wire. This means more energy over the line and therefore will cut down slightly the distance over which operation may be obtained. In increasing the number of operations over a given system, the number of wires would not increase but the number of relays in the system can take care of the increased number of operations.

**E. I. Greene:** Could lower frequency than 70 cycles on the pulsator of the two-wire system be used?

**M. E. Reagan:** It could be through any reasonable frequency. A vibrator producing 16 cycles has been used successfully.

# High-Velocity Vapor Stream in the Vacuum Arc

BY R. C. MASON[*]
Associate, A.I.E.E.

*Synopsis.*—*The discovery and importance of a high-velocity vapor stream issuing from the cathode region of a vacuum arc led to a summary of the experiments showing the existence of a vapor stream and a review of the theories proposed to account for it.*

*The velocities were determined from: (1) force on the cathode and loss weight by the cathode; (2) force on a vane in front of the cathode, and mass of cathode material deposited on the vane; and (3) energy imparted to vane, and mass of material deposited. Methods (1), (2) and (3) on the copper arc gave vapor velocities from 1 to 2.5* $\times 10^6$ *cm/sec, while method (1) on a mercury arc gave an average of* $2.24 \times 10^6$ *cm/sec. Sources of error would not change the above values greatly.*

*Several proposed theories are shown to be inadequate; the one possible theory (Risch and Lüdi) is based upon the presence of multiply-charged ions which leave the cathode after neutralization with a high velocity.*

IN the last few years it has been discovered that a blast of vapor issues at high velocity from the cathode region of a vacuum arc. The consideration of this subject is important in the study of the arc. Previous theories of the cathode of an arc, which have not taken account of the vapor stream, must be extended, for the vapor blast, as it now appears, is a part of the cathode phenomena, and as such must be included in any satisfactory theory of the cathode of an arc. The energy carried away in the high-velocity vapor stream, which is not an inconsiderable part of the total energy loss at the cathode, must be included in the heat balance at the cathode. This paper will review the experimental evidence for the existence of the vapor blast, and will discuss the theories proposed to explain its origin.

By "vacuum arc" is meant an arc between metal electrodes in a residual gas at low pressure—a few microns or less. Such an arc burns, near the cathode at least, primarily in the vapor of the cathode material. Vapor of the cathode metal leaves the cathode region with a velocity over $10^6$ cm/sec. Such velocities in themselves are not extraordinary, but in the arc their origin is a matter of wonder. The velocities correspond to equivalent volts[†] of 36 to over 500—several times the total arc voltage—so that a direct electrical origin is not obvious. Several different methods of observation, described below, yield results of the same magnitude, however.

## EXPERIMENTAL RESULTS

The existence of the high-velocity vapor stream was first discovered by Tanberg[1] who observed and measured a force of considerable magnitude on the cathode of a vacuum arc. A copper rod, suspended freely by a fine wire, as shown in Fig. 1, served as the cathode of the arc. Before the arc was drawn by moving the anode into contact with the cathode, the pressure in the vessel was about 0.2 micron; at the end of a test of a few seconds duration, the pressure had increased to some 10 microns. When the arc was burning the reaction on the cathode caused a deflection of the whole cathode structure; from the length of support and the deflection, the force on the cathode was found. The cathode was weighed before and after a test of known duration so that the loss of weight per second was known. The force is equal to the change of momentum—the mass of vapor escaping per second times its mean velocity. The velocity determined in this way was $1.04 \times 10^6$ cm/sec, as the average of several tests.

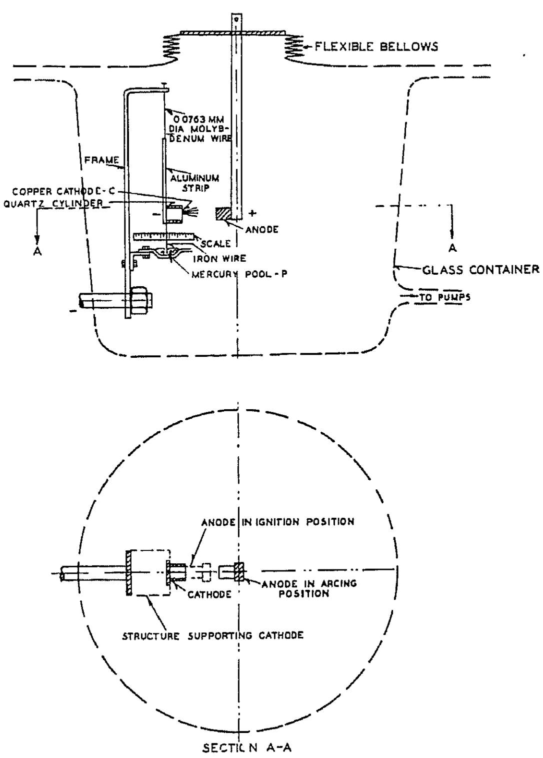

FIG. 1—APPARATUS FOR DETERMINATION OF CATHODE VAPOR SPEED

By another method also, Tanberg measured the vapor velocity. A glass vane was suspended 2 cm before a fixed cathode. With an arc playing, the vapor issuing from the cathode caused the vane to deflect. From the vane deflection and the mass of copper vapor deposited on the vane per second, the mean velocity of the vapor striking the vane was found to be about 1.35 × $10^6$ cm/sec.

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[†] The volt equivalent of the velocity of a particle is the potential through which a singly charged particle of the same mass must fall in order to acquire the same velocity. It is calculated from $eV = \frac{1}{2}mv^2$.

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[1] *Phys. Rev.*, **35**, 1080, 1930.

Kobel[2] observed a large force at the cathode of a mercury arc, and in a similar way calculated a high velocity for the vapor leaving the cathode. The mercury level in a conical tungsten cup was adjusted until the cathode spot just covered the entire mercury surface. The difference in level of the mercury in the cathode cup and in a connecting side tube, shown schematically in Fig. 2, represented the force on the cathode. The loss of mercury from the cathode was measured by observing the rate of change of mercury level in the tungsten cup. From these two quantities the mean velocity of the vapor leaving the cathode region can be calculated. Values from 1.15 to 3.1 × $10^6$ cm/sec are obtained, with an average of 2.24 × $10^6$ cm/sec.

All of the results mentioned above were obtained from measurements of momentum, though the way in which the balancing force was read differed slightly. Berkey and Mason,[3] however, measured the *energy* of the vapor stream. The experimental arrangement is shown in Fig. 3. A silver vane was suspended in front of the cathode of a copper vacuum arc. To the side of the vane away from the cathode, a thermocouple was soldered. The thermocouple gave the rise in temperature during a period of arcing; from the rate of rise of the temperature and the thermal capacity of the vane the energy input to the vane was calculated. The mass of copper deposited on the vane was determined by weighing. These two quantities permitted the rms velocity of the vapor striking the vane to be calculated. The values obtained lie between 1.74 and 2.46 × $10^6$ cm/sec with an average of 2.04 × $10^6$ cm/sec. The deflection of the vane was also obtained in these tests, and the mean velocity of the vapor calculated as 1.62 to 3.7 × $10^6$ cm/sec, with not very great accuracy.

*Sources of Error and Corrections*. Several corrections have been made or considered in attempting to eliminate sources of error in measuring the vapor velocity. The most obvious, that of the electrodynamical force on the cathode resulting from the disposition of the current leads was estimated by Tanberg and deducted before the values of velocity given above were calculated. A further electrodynamic force, resulting from the convergence of current flow at the cathode spot, was estimated by Risch[4] to be not over 5 per cent of the measured force. The radiation pressure on the cathode was an entirely negligible factor. The reaction pressure of the electrons leaving the cathode was not over 5 per cent of the total force, as pointed out by Risch.[4] Thus, of the forces upon the cathode measured by Tanberg and Kobel not over about 10 per cent can be attributed to causes other than the reaction of the vapor leaving the cathode region.

None of the above mentioned corrections are applicable to the force on the vane suspended in front of the arc. The mean velocity calculated for the vapor striking the vane can be in error only if the mass involved is incorrect—that is, if some of the vapor striking the vane is reflected without condensation. This seems hardly probable as metal vapors usually condense with little reflection. Furthermore, the amount of copper deposited on the vane was just the amount to be expected if a cosine distribution of the measured loss of material from the cathode existed; and the density of vapor deposited on the walls of the containing vessel followed a cosine law. No great amount of reflection thus seems reasonable. If such did occur, the rms velocity would be more nearly correct than the mean velocity; actually about the same values are secured for each.

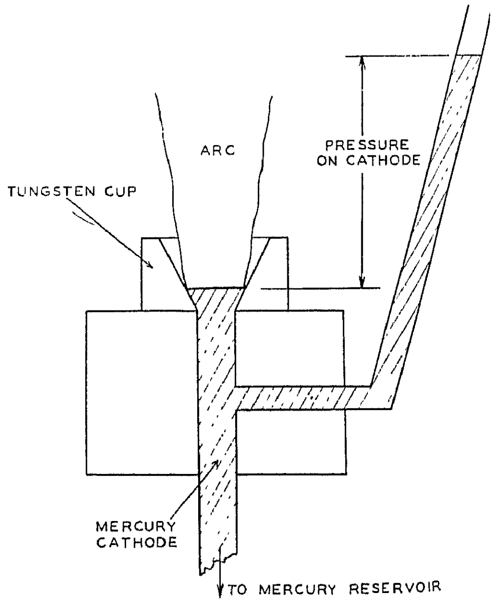

Fig. 2—Kobel's Experiment

The vane may receive energy from the arc, in addition to the energy of the impinging vapor, by radiation and by recombination of ions upon the vane. The radiation energy received was measured experimentally, found to be small, and was subtracted from the total before the rms velocity quoted was calculated. An upper limit to the latter energy would be obtained by considering all the vapor condensing as ionized. Then the energy of recombination would amount to less than 10 per cent of the total.

Other sources of error lie only in inherent difficulties in reading the experimental quantities. While the masses involved could be determined exactly, deflection methods probably permitted no great accuracy in determination of the forces; and Kobel records difficulty in adjusting the mercury levels. It is probable that the energy measurements yield more accurate values of the velocity of the vapor stream than the other methods.

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[2] *Phys. Rev.* **35**, 1636, 1930.

[3] *Phys. Rev.* **38**, 943, 1931.

[4] *Helv. Phys. Acta.* **4**, 122, 1931.

Some of the quantities observed by the different investigators are given in the table. The volt equivalent of the velocity is given in order to aid in explaining the theories offered. For the energy measurements this quantity may be calculated directly; but the mean velocities should be translated into rms velocities before calculating the volt equivalents. A knowledge of the velocity distribution would be necessary in order to get the ratio of rms to mean velocity; for a uniform velocity distribution the ratio is one, while for any other distribution the ratio is greater than one. Since the actual distribution is entirely unknown, the minimum value is the one used in the following table.

## THEORIES

Several theories have been put forward to account for the origin of the high velocity of the vapor. The temperature of the cathode spot is inadequate to give the emitted vapor the velocities calculated. The temperature of the cathode spot of the copper vacuum arc has been estimated to be under 3,000 deg K,[5] while in the mercury arc the cathode temperature is probably only a few hundred degrees. The vapor velocities, however, are the same magnitude as the average molecular velocity of a gas in thermal equilibrium at several hundred thousand degrees so that a purely thermal origin of the high speeds seems impossible.

| Observer | Arc | Method | Range of data: Current amperes | Range of data: Force dynes | Range of data: Mass involved | Results—average of several tests: Mean veloc cm/sec | Results—average of several tests: Equiv. volts |
|---|---|---|---|---|---|---|---|
| Tanberg | Copper | Force on cathode | 11 to 32 | 189 to 435 | Avg $1.5 \times 10^{-5}$ gr/amp-sec | $1.04 \times 10^6$ | 36 |
| | | Force on vane | 14 to 18 | 63 to 92 | 4.3 to $6.5 \times 10^{-5}$ gr/sec | $1.35 \times 10^6$ | 60 |
| Kobel | Mercury | Force on cathode | 30 to 37 | 687 to 1,700 | Avg $1.7 \times 10^{-5}$ gr/amp-sec | $2.24 \times 10^6$ | 520 |
| Berkey and Mason | Copper | Force on vane | 20 | 36 to 70 | 2.22 to $2.38 \times 10^{-5}$ gr/sec | $2.48 \times 10^6$ | 202 |
| | | Energy imparted to vane | 20 | Energy 3.59 to $7.26 \times 10^7$ ergs/sec | 2.22 to $2.38 \times 10^{-5}$ gr/sec | rms veloc $2.04 \times 10^6$ cm/sec | 137 |

*Wellman's Theory.* Wellman[6] suggested that, though the reaction of the copper leaving the cathode at 3,000 deg K was small, the reaction of gas evolved from the cathode during arcing might account for the remainder of the observed force. His calculations were based upon an incorrect value of current, however, so that the actual force of the gas is also a small factor. Furthermore, the mass involved in calculating the high velocities was determined by weighing the cathode before and after arcing so that any net loss of gas was included with loss of copper; only gas evolved during arcing and reabsorbed before the subsequent weighing of the cathode would not be discerned. In the mercury arc it seems unlikely that any gas was evolved from the cathode.

*Compton's Theory.* It has been shown by different methods[7, 8] that positive ions drawn to an electrode by an electric field are neutralized but give up to the electrode only part of the kinetic energy acquired from the field; part of the energy is retained and carried away by the neutral molecule. From the similarity to heat and momentum exchange of a gas with a solid the ions are said to possess an "accommodation coefficient" less than unity. Compton proposed that the existence of an accommodation coefficient, whereby neutralized ions leave the cathode with considerable momentum, could account for the reaction upon the cathode of a vacuum arc.

In effect, by this theory a more dense stream of low-velocity particles is substituted for the less numerous high-velocity particles of Tanberg and Kobel. Since the mass of positive ions striking the cathode per second might be much larger than the mass of the net vaporization from the cathode, the observed reaction could be accounted for if the neutralized ions left the cathode with a small part of the energy acquired from the cathode fall space. Compton calculated that a retention of only 2 per cent to 5 per cent of the incident energy—less than 0.5 equivalent volt—would be necessary for the copper and mercury arcs, if half the current were carried by positive ions; if a smaller part of the current were carried by positive ions, then the accommodation coefficient would have to be still smaller. While small values do exist for light atoms, the accommodation coefficient for heavy ions, such as copper or mercury, has not yet been measured.

Even though the mechanism suggested by Compton may possibly picture correctly the way in which the reaction is imparted to the cathode, it has been pointed out[4, 9] that the necessity of a high-velocity vapor stream leaving the cathode region remains. The force on the cathode must be balanced by the momentum of the particles escaping from the cathode region; since a low pressure existed during the experiments, the flow of momentum can be carried only by the vapor corresponding to the net loss in weight of the cathode. Consequently, the velocity calculated for this vapor must be correct. The suggestion offered would not account for the high-speed vapor striking the vane before the cathode. If the Compton theory is valid, then an equal difficulty remains in devising a way by which the many molecules with low velocity may transfer their momentum to a few molecules with high velocity.

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[5] *Phys. Rev.* **38**, 296, 1931.

[6] *Phys. Rev.* **38**, 1077, 1931.

[7] *Phys. Rev.* **37**, 1596, 1931.

[8] *Phys. Rev.* **37**, 842, 1931.

[9] *Phys. Rev.* **37**, 779, 1931.

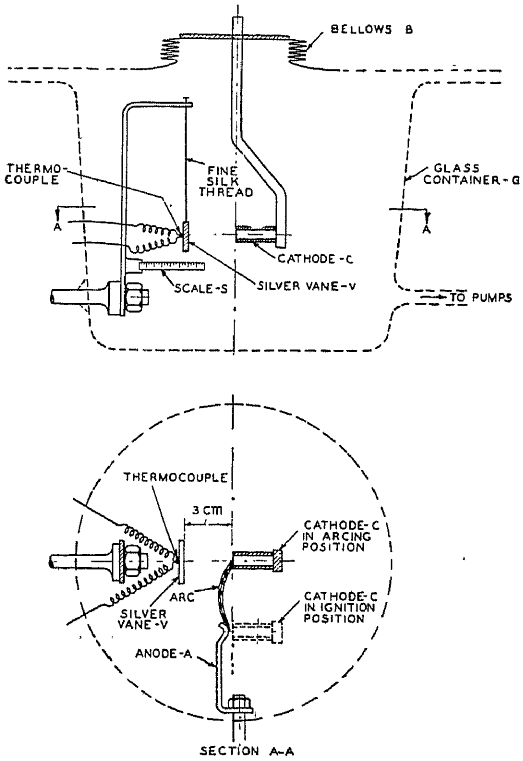

Fig. 3—Apparatus for Measurements on Cathode Vapor Stream

*Risch and Lüdi's Theory.* Risch and Lüdi[10] have recently proposed a theory, somewhat like Compton's theory, but avoiding the difficulties there encountered. An electrical mechanism is provided for the attainment of high velocity by the particles leaving the cathode region. Positive ions incident upon the cathode possess both kinetic energy, acquired from the field, and potential energy, in virtue of their ionization. Risch and Lüdi propose an accommodation coefficient for the potential energy; that is, positive ions are neutralized at the cathode but some of the energy set free in this act is presumed to be converted into kinetic energy of the neutral particle. Most of the atoms evaporated from the cathode are ionized and drawn back before escaping completely; after neutralization, they leave at a high velocity. Upon this assumption, the ion current is equal to the net material loss from the cathode. In order to supply thermal losses from the cathode and to provide for the large kinetic energy of the escaping vapor, it is necessary to suppose that the positive ions are multiply charged—that they have been ionized six or seven times. This Risch and Lüdi believe possible, because such a dense stream of electrons is coming from the cathode that a copper atom would be struck many times while it remained in the cathode region, and the time intervals between collisions would be too short for the atom to radiate away the energy received from the electrons. Thus ionization would proceed by cumulative action until an ion would possess several hundred volts potential energy. Risch and Lüdi's calculations for the copper arc run briefly thus: If 86 per cent of the current is carried by electrons (see below) a current density of 14,000 amp/cm$^2$ corresponds to $7.5 \times 10^{22}$ electrons/cm$^2$-sec. If the cross-section of a copper atom is $10^{-15}$ cm$^2$, each atom will be struck $7.5 \times 10^7$ times per sec, and the mean time between two impacts is about $10^{-8}$ sec—too brief for radiation to occur. The energy lost from the cathode by conduction is taken as 3 watts/amp, and by electron cooling as 7 watts/amp. The loss of $1.5 \times 10^{-5}$ gr/amp-sec of copper is equal to $1.4 \times 10^{17}$ molecules/amp-sec, so if this is taken equal to the ion current,

$$\frac{1}{1.4 \times 10^{17} \times 1.59 \times 10^{-19}} = 44$$

elementary charges must be conveyed per ion. If the ions bear six charges, then 38 electrons (or 86 per cent of the current) must be freed for each positive ion. If the energy of the departing neutralized ion is 140 equivalent volts, then the total energy loss per ion is $(7 \times 38) + (3 \times 44) + 140 = 540$ volts. Of this, kinetic energy can provide $6 \times 15 = 90$ volts (six-fold charge times assumed 15 volts cathode fall), leaving 450 volts to be supplied as potential energy—corresponding to 6 or 7 times ionized. Since an electron would have only 15 volts energy at the cathode fall boundary, at least 30 electron impacts per ion formed is necessary. This would involve only $30 \times 10^{-8}$ sec, too short a time for the ion to move far.

The cross-section for excitation of an atom is considerably less than the kinetic theory cross-section used above, so the time between exciting collisions might possibly be longer than the mean time of existence of an excited atom without radiation. Though this and other minor objections might be raised, at present there seems to be no definite proof of the impossibility of the explanation of Risch and Lüdi. Indeed, in the arc where the energy density is so much greater than in other forms of discharges, it would not be surprising to find higher states of ionization than exist in other discharges. The idea of multiple ions is entirely new to the theory of the arc cathode, and certainly must be taken into consideration as a possibility in the formulation of a theory of the cathode. Any complete theory of the arc must embody an explanation of the origin of the high velocity vapor stream.

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[10] *Zeits. f. Phys.* **75**, (No. 11/12) 812, 1932.

## Discussion

**Elmer C. Easton and Frank B. Lucas:** Mr. Mason's paper has discussed the high velocity vapor stream emitted from the cathode of a vacuum arc. It makes no mention of a similar vapor stream leaving the anode.

At Lehigh University we have conducted experiments to determine the force acting on the electrode of an iron arc in vacuum. Our apparatus consists of two fixed electrodes and one moving electrode mounted in a tank from which the air can be exhausted. The moving element consists of a cylindrical aluminum disk floating in a cup of mercury and fitted with a brass rod which extends radially from the float and which terminates in a clamp through which is passed an iron electrode at right angles to the brass radius rod. The float is counterbalanced so that the electrode is free to revolve in the mercury pool. By passing current through the mercury, an arc can be struck between one fixed electrode and the moving electrode. The arc force causes the moving element to rotate. By applying the current for a short measured interval the moving element can be given an impulse whose value is indicated by the amount of rotation of the moving element. The instrument has been calibrated by means of a pendulum.

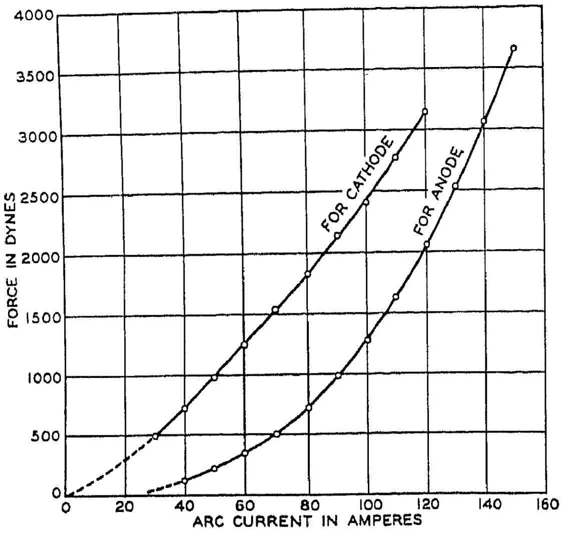

Fig. 1

The force observed was found to differ with the polarity of the moving element. The curves in Fig. 1 show the relation between arc forces and current for each polarity. These observations were part of a preliminary study and were made at a pressure of about five millimeters of mercury. It will be noticed that the force on the anode is very small for current values below 40 amperes.

In order to determine whether or not a high velocity vapor stream was emitted from iron electrodes, a light vane was attached to the end of the moving electrode and the arc struck between the two fixed electrodes. By the same procedure as used by Tanberg and mentioned in Mr. Mason's paper, we calculated the velocity of the vapor streams which were found to come from *both* anode and cathode. Using short current shots of approximately 300 amperes in a pressure of 5 mm Hg, the velocity of the anode stream was found to be about 16 x $10^4$ cm per sec while that of the cathode stream was 23 x $10^4$ cm per sec. It is thought that these velocities would have been higher had the pressure in the tank been less. In the work that will be done when the difficulties encountered in these preliminary tests are overcome, the forces and velocities will be measured in a much better vacuum. The following table shows some of the preliminary test data.

| Arc | Method | Current amperes | Force dynes | Mass gm/sec | Electrode | Rms velocity cm/sec | Pressure mm Hg |
|---|---|---|---|---|---|---|---|
| Iron | Force on vane | 300 | 2,513 | 0.0153 | Cathode | 22.8x$10^4$ | 5 |
| Iron | Force on vane | 302 | 1,435 | 0.0126 | Anode | 15.8x$10^4$ | 5 |

The results of our work so far lead us to suggest that the current values used by Mr. Mason and others working with the arc be increased. Apparently the anode forces are almost unobservable at the low current values (30 amperes) used by Tanberg, Mason and Berkey, and Kobel.

**F. Creedy:** What are the author's precise reasons for supposing that these jets consist of vapor? More than 30 years ago Bredig showed that colloidal particles were emitted by a metal arc operating in a fluid and that these would form an emulsion with the fluid. Is it not at least possible that it is these colloidal particles that we are observing? The surprisingly great magnitudes of these forces and the large amount of material deposited when we use large currents make it difficult to believe that this passes in the form of vapor. I have no suggestions to make as to the mechanism which causes these particles to be projected.

**R. C. Mason:** Previous experiments on the vapor stream from the cathode of the vacuum arc have not been arranged, so far as the writer is aware, in such a way as to test the presence of a similar stream from the anode. At pressures of a few microns, the current and energy densities at the anode are quite small compared to those at the cathode, so it would be surprising to find an anode vapor stream of velocity equal to the cathode stream.

Of course, at low pressures, the cathode vapor jet would impinge on an oppositely placed anode and impart a momentum to it, even if the anode were not emitting a high velocity stream of vapor. In a high vacuum, if the distance between electrodes were small compared to their dimensions, the force on the anode would be just equal and opposite to the force on the cathode. With gas present, the force on the anode would be expected to be less than that on the cathode, and the difference should be greater the higher the pressure and the greater the distance between electrodes, because of the scattering of the cathode vapor stream.

Without the details of the experiment of Messrs. Easton and Lucas using a vane, I am unable to offer any suggestions as to the origin of the apparent anode vapor stream. If an anode stream of velocity almost equal to the cathode vapor jet should be found real, an explanation of its mechanism would seem even more difficult to devise than does an explanation for the cathode stream.

No microscopic examination of the material deposited from the cathode has been made, but it seems reasonable to me that in the cathode region at least the material exists in vapor form. Conditions in the vacuum arc differ so greatly from conditions in an arc in a liquid, it seems improbable that colloidal particles such as exist in the latter are ejected from the former. Whatever the size or mass of the particles of cathode material, however, the velocity calculated would be the same.

# New Studies of the Arc Discharge

BY J. LELAND MYER*

***Synopsis.***—*The equation $V = A + B/I^n$ which correctly represents all normal arc characteristics is used as the starting point for a general discussion of arc phenomena and industrial applications.*

*Tests of this equation are applied to iron arcs in various gas atmospheres to obtain a series of values for A and B, making possible certain deductions about arc voltage variations and significance of the characteristics.*

*In limiting the current exponent n, the anode temperature must exert considerable influence on the discharge as a whole. Suggestions are given why this may be so. A value of n is predicted from the arc stream geometry, and is compared with actual values of n for various arcs.*

*From energy considerations of this equation new concepts of the "minimum energy" and the "excess energy" requirements in the arc conduction process are gained. Some applications to arc problems prove these concepts valuable. On this basis high temperature arcs are shown to be the most efficient.*

*Light intensity and probe measurements on the arc stream suggest a new physical picture of high current arcs. Some difficulties are removed in accounting for energy equilibrium at the welding arc cathode.*

For nearly a century the phenomena of the electric arc have been studied from the viewpoints of classical physics and commercial application. Keen interest has recently given a strong impetus to investigations in both fields, so that the already copious literature of the past has been greatly enlarged. Unfortunately from all this work there has been little crystallization of opinion about certain phases of the fundamental arc theory. Many details of the exact discharge mechanism have evaded discovery for a long time, so that our basic concepts are not yet complete.

For physicists the electric arc presents an important field for studying the atom and electron. In the laboratory therefore attention has been confined to arcs on a small scale, usually under the simplest and most desirable conditions for experiment. The interesting phenomena at the cathode are now well understood, and many pertinent features of the discharge have been rather fully investigated. Probably the best survey of this subject has been given in an excellent paper by Professor K. T. Compton.[1]

Arcs used in engineering practise and industrial applications are much more complicated than those studied by the physicists. While simplicity and understanding of the phenomena are not the prime considerations in experimenting with such arcs, it is surprisingly true that commercial practise is often far in advance of theory. There can be little doubt however that more rapid progress might result under the guidance of theory and basic experiments properly executed. The present paper deals with some considerations which may bring theory and practise into somewhat closer agreement.

## THE CORRECT ARC EQUATION

There is hardly another item connected with arc research that has received as much attention, both in point of time and number of investigators, as the characteristic equation of voltage, current and arc length. It may well serve as a starting point for a more general discussion of the discharge.

Ayrton[2] was able to write a successful equation of the form

$$V = A + B/I \tag{1}$$

for the static characteristic of the carbon arc. For energy considerations (1) becomes

$$VI = AI + B \tag{2}$$

expressing the total energy input as some constant plus a linear function of the current for carbon arcs of given length. When applied to the characteristics of metal arcs (1) was a close approximation if the constants $A$ and $B$ were properly adjusted. But the equation was valid only over limited portions of the characteristics, and could not be made to represent them entirely.

In their investigations on metal arcs Malcolm and Simon[3] pointed out that the total energy *vs.* current relations were not straight lines, as equation (2) would indicate, but they were curves slightly concave to the current axis. Steinmetz[4] was able to prove that the characteristics were definitely hyperbolic, but in place of (1) could be better represented by a general equation

$$V = A + B/\sqrt{I} \tag{3}$$

Such equations likewise were limited in their application, and were not truly general for all arcs.

It remained for Nottingham[5] through a systematic study of numerous arc characteristics to establish a correct general equation of the form

$$V = A + B/I^n \tag{4}$$

which, it will be noted, differs only in the current exponent $n$ as compared to (1) and (3). This current exponent is a variable and, curiously enough, has been found to *vary directly with the boiling or sublimation temperature of the anode material* by the relation

$$n = 2.62\,(10)^{-4}\,T \tag{5}$$

The fact that carbon boils at 3,770 deg $K$ (Van der Waals) gives the exponent $n$ a corresponding value of 0.987, making equations (1) and (4) almost identical

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*Engineering Foundation Research Fellow on research being conducted by the laboratories of Lehigh University under the direction of Dr. Gilbert E. Doan.

1. For numbered references see bibliography.

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for carbon arcs, and explaining the early success of the former.

The validity of equation (4) can best be tested by making a logarithmic plot of $(V - A)$ *vs.* $I$. If the data support this test, the points will lie on straight lines of negative slope $n$. Such tests are most easily carried out on those portions of the arc characteristics between one and ten amperes current and one to ten mm arc length. For currents below one ampere the voltage is usually unstable. Above ten amperes the electrodes melt rather rapidly, and also the term $(V - A)$ becomes vanishingly small as the voltage begins to approach its limiting value

$$V = A \tag{6}$$

a relation known to exist in heavy current arcs. Arc lengths less than one mm and greater than ten mm introduce further difficulties in obtaining accurate values of voltage and current. Nottingham has successfully applied equation (4) to many normal arcs over this range of the characteristics. In addition to the original work there is further verification by Anderson and Kretchmar[6] and by Doan and Myer.[7] The positive results of these numerous tests establish (4) as a true general equation for normal arcs, and its correctness has never been questioned.

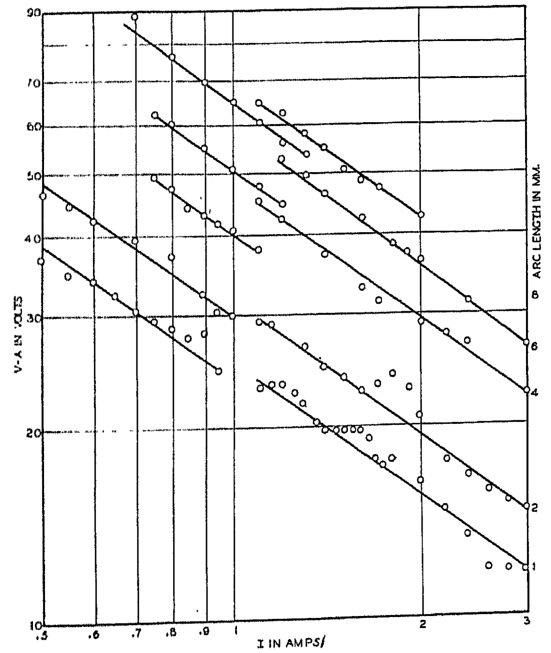

Fig. 1—Test of Equation for the Iron Arc in Air (Cady and Arnold Data)

IRON ARC IN AIR
First Stage

| $L$ | $A$ | $B$ | $n$ |
|---|---|---|---|
| 1 | 29.1 | 23.5 | 0.71 |
| 2 | 37.5 | 30.4 | 0.71 |
| 4 | 43.0 | 40.6 | 0.73 |
| 6 | 46.0 | 50.7 | 0.74 |
| 8 | 47.3 | 64.0 | 0.73 |

IRON ARC IN AIR
Second Stage

| $L$ | $A$ | $B$ | $n$ |
|---|---|---|---|
| 1 | 19.1 | 27.7 | 0.69 |
| 2 | 21.5 | 35.6 | 0.69 |
| 4 | 24.0 | 50.2 | 0.71 |
| 6 | 25.1 | 60.8 | 0.73 |
| 8 | 26.6 | 72.5 | 0.72 |

Unfortunately nothing further has resulted from the discovery and verification of this equation. Physicists have long considered emission at the cathode as the essential and controlling feature of the discharge, since all other phenomena appear to be either consequences of this emission or prerequisites to it. The influence of the anode temperature was completely unsuspected and, so far as the writer is aware, has never been explained. However, there is reason to believe that the marked success of this equation may well indicate an important and predominating role of the anode temperature which may give new clues about the discharge mechanism. Before discussing this point directly it may be well to examine some tests of the equation (4) in the hope of enlarging our ideas about its functioning and possibly its interpretation. To gain a complete understanding would require an examination of numerous arcs under systematically varied conditions. For the present study the existing data on short, low current arcs between iron electrodes in various gas atmospheres must suffice.

## Equation Applied to Iron Arcs

The arc between iron electrodes in air is known to make a transition from a first (high voltage) stage to a second (normal voltage) stage at about one ampere. This transition was investigated by Cady and Arnold[8] whose experiments show the excess voltage of the first stage to lie in the anode fall. This is attributed to a temperature equilibrium at the anode which is below the limiting value of the boiling point. It will be interesting to apply the test of equation (4) to both stages, and note whether the value of $n$ gives any indication of such temperature conditions at the anode.

Fig. 1 is a test of the original data, and demonstrates that the equation applies not only to the second (normal voltage) stage as was previously known, but also to the first (high voltage) stage. The constants $A$ and $B$ are different for the two stages, as must be expected from the different positions of the characteristics, but the values of $n$ are the same, and therefore imply equal anode temperatures in both stages.

The writer's data for the iron arc over both stages differ slightly from Cady and Arnold's, possibly because the electrodes were smaller and of different quality metal. The data likewise confirm the tests of equation but with different values of $A$ and $B$.

The normal iron arc has been found to operate very steadily at low voltage in atmospheres of the inert gases argon, helium and neon, when slight contaminations of the gas or electrodes are present. (Under conditions of rigid purification, Doan and Myer[9] have found it impossible even to strike an arc in inert gases.) With impurities present in all three gases the test of the equation is supported equally as well as for the iron arc in air. Fig. 2 shows these tests for the arc in helium. In argon and neon the results are very similar, with lower values of $A$ and $B$.

From these tests there now exists a series of determinations for the constants $A$ and $B$ of the iron arc in various gas atmospheres and in different stages of the characteristic. A comparison may give some idea about their significance and interpretation.

### THE SIGNIFICANCE OF $A$ AND $B$

In Fig. 3 are given the variations of $A$ and $B$ with the arc length. For these short arcs the values of $A$ may be extrapolated toward zero arc length, if this be regarded only as an elimination of the effects of the discharge stream. (There is evidence that the anode and cathode falls cancel off as the electrodes actually approach zero arc length.) So extrapolated, the curves for $A$ are seen to converge toward a common point $A_o$ = 15 volts. Therefore it is likely that *$A_o$ is basically characteristic of the electrode material.* If the effects of the arc stream have been eliminated, $A_o$ might then represent the combined anode and cathode falls, or at least that portion of them which is independent of current.

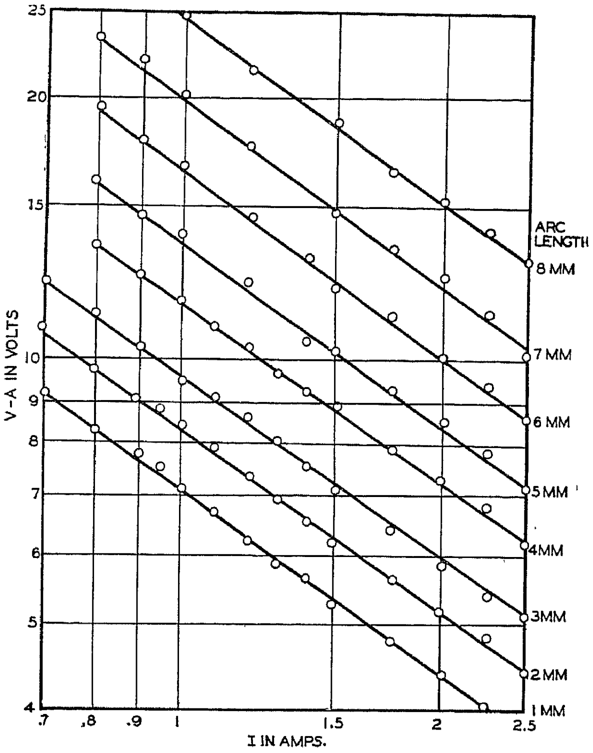

FIG. 2—TEST OF EQUATION FOR THE IRON ARC IN HELIUM

IRON ARC IN HELIUM

| $L$ | $A$ | $B$ | $n$ |
|---|---|---|---|
| 1 | 16.6 | 7.1 | 0.701 |
| 2 | 17.8 | 8.3 | 0.705 |
| 3 | 18.4 | 9.5 | 0.709 |
| 4 | 19.7 | 11.4 | 0.717 |
| 5 | 20.4 | 13.7 | 0.714 |
| 6 | 21.4 | 16.4 | 0.720 |
| 7 | 21.9 | 20.0 | 0.722 |
| 8 | 22.6 | 24.7 | 0.728 |

The lack of extensive data makes it impossible accurately to check the value of $A_o$ on this assumption. Child[10] has measured the cathode fall of an iron arc as 13.9 volts and Grotrian[11] as 15 volts. Both values were obtained with the uncorrected probe method, and may not be correct. For the mercury, cadmium and thallium arcs the cathode falls have been more accurately determined, and are about equal to the ionization potential of the metals. This analogy might be carried to the iron arc, except that the ionization potential for iron is variously given as 5.3, 6.5 and 7.8 volts. An approximate check may be made from the known drop of 17 to 19 volts across heavy current iron arcs of very short length. Allowing several volts for the arc stream fall, 15 volts seems to be of the right order for the combined anode and cathode falls at high currents.

To explain the increase of $A$ with arc length the anode and cathode falls are not sufficient. The cathode fall is believed to be independent of current, and also of arc length except when the length approaches zero. The anode fall may vary widely, even taking on negative values as explained by Langmuir, but is not known to increase with arc length as rapidly as the curves rise. The added increase of $A$ must result from *some conditions in the arc column which are independent of current variation.*

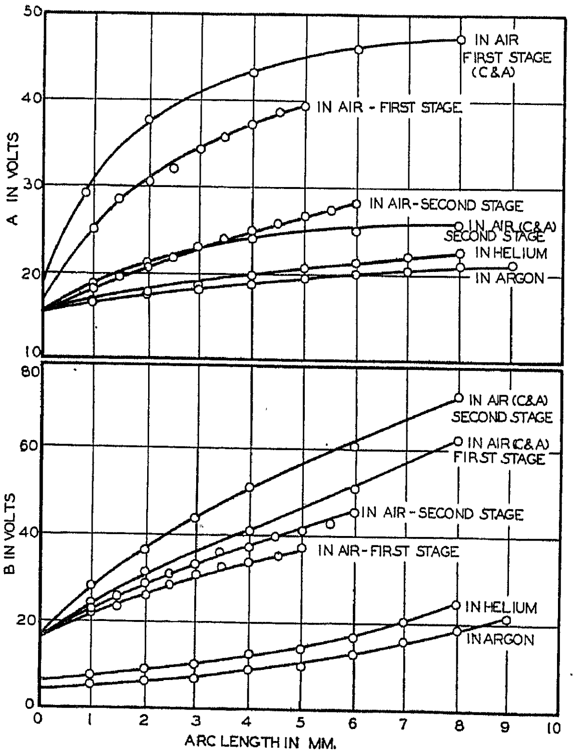

FIG. 3—VARIATIONS OF $A$ AND $B$ WITH ARC LENGTH

The values of $B$ show the variations of this constant to be strongly influenced by the *nature of the gas* in which the arc is operated. Similarly extrapolated, $B_o$ differs for each gas, and may be an index for the initial rate of change of the anode fall (possibly the cathode fall also) occurring in each gas. For air the variation of $B$ is nearly linear, and therefore representative of conditions in the arc column which change with length. For the inert gases $B$ increases more rapidly than the linear rate with arc length, and may be connected in some manner with the elastic impacts in inert gases which are known to alter conditions in the arc column.

Altogether the variations of $B$ with arc length do not give a very clear picture. It must be remembered that $B$ is primarily an *index of those factors which vary with the arc current,* and its significance becomes plainer when considered in connection with equation (4) where it occurs in the term $B/I^n$. It will later be shown that this term has the nature of an *efficiency factor in the current conduction process* of the discharge.

Experiments reveal that the complete relation between voltage, current and arc length cannot be expressed by an equation less complex than

$$V = \left(\alpha_\infty + \frac{(\alpha_1 - \alpha_\infty)}{I^n}\right)\left(1 - \epsilon^{-dL}\right) + \left(\beta_\infty + \frac{(\beta_1 - \beta_\infty)}{I^n}\right)\left(1 - \epsilon^{-\left(\delta_\infty + \frac{(\delta_1 - \delta_\infty)}{I_n}\right)L}\right) + \left(\gamma_\infty + \frac{(\gamma_1 - \gamma_\infty)}{I^n}\right)L \qquad (7)$$

of which (4) is a special form when $L$ is constant. In equation (7) the term $(1 - \epsilon^{-dL})$ provides for a cancellation effect of the anode and cathode falls when the arc is exceedingly short. For normal arcs above one mm length this term becomes unity and may be removed from the general expression.

$$\left(\gamma_\infty + \frac{(\gamma_1 - \gamma_\infty)}{I^n}\right)L$$

gives the variation of $A$ and $B$ with length of the positive column.

$$\left(\beta_\infty + \frac{(\beta_1 - \beta_\infty)}{I^n}\right)\left(1 - \epsilon^{-\left(\delta_\infty + \frac{(\delta^1 - \delta_\infty)}{I_n}\right)L}\right)$$

is either the total anode fall, or the variation of the anode fall with arc length and the rate of change of that variation with arc current. No systematic tests have ever been made to verify this assumption, but some few calculations have shown that it does not express the anode fall as measured. Therefore the first term

$$\left(\alpha_\infty + \frac{(\alpha_1 - \alpha_\infty)}{I^n}\right)$$

may include some portion of the anode fall in addition to the total cathode fall.

The deductions made from Fig. 3 and equation (7) give some idea of the manner in which $A$ and $B$ operate correctly to represent the arc characteristic. Quantitative measurements in individual portions of the arc discharge are greatly needed to make this interpretation complete and exact. When these become available it should be possible to replace equation (7), which was derived purely from graphical analysis of the characteristic curves, by an equivalent expression which clearly represents the exact conditions and variations throughout the arc discharge.

### SIGNIFICANCE OF THE EXPONENT $n$

While $A$ and $B$ have been found to vary in a not too simple manner, the exponent $n$ should be a constant according to the equation

$$n = 2.62\,(10)^{-4}\,T \qquad (5)$$

If $n$ really depends upon a temperature effect extending from the boiling anode into the positive column, a variation might be anticipated with increasing arc lengths. Optical pyrometer measurements on ten-ampere carbon arcs[12] register temperature variations of over 2,000 deg $C$ in the positive column, although there is an indication of constant temperature over considerable portions of the discharge.

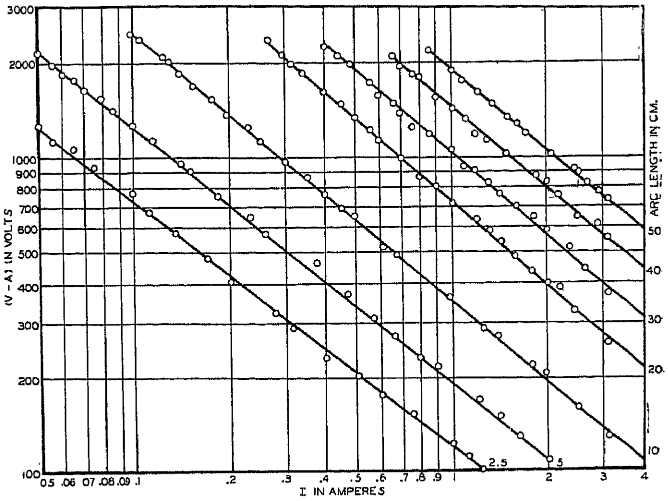

FIG. 4—TEST OF EQUATION FOR THE IRON ARC IN AIR

| $L$ (cm) | $A$ | $B$ | $n$ |
|---|---|---|---|
| 2.5 | 50 | 117 | 0.77 |
| 5.0 | 70 | 190 | 0.81 |
| 10.0 | 110 | 345 | 0.85 |
| 20.0 | 180 | 720 | 0.88 |
| 30.0 | 260 | 1,050 | 0.89 |
| 40.0 | 350 | 1,440 | 0.90 |
| 50.0 | 400 | 1,910 | 0.91 |

This point can perhaps best be tested by using Grotrian's[11] data on low current, high voltage, iron arcs of great length in air. Such arcs might still be considered as normal arcs, except for the fact that the anode was water-cooled to prevent rapid melting. (Nottingham found that when the anode of tungsten arcs was below the boiling temperature, the exponent $n$ was below the normal value.) In Fig. 4 Grotrian's data are shown to support the test of equation, but the values of $n$ are above normal, increasing with the arc lengths.

Normal arcs of shorter length also exhibit systematic variations of $n$ as given in Table I. The general tendency is for $n$ to approach unity, as if this fulfilled some

TABLE I—VARIATION OF $n$ WITH ARC LENGTH IN NORMAL ARCS

| Arc length mm | W in air | Cu in air | Fe in argon | Fe in helium |
|---|---|---|---|---|
| 1 | | | 0.700 | 0.701 |
| 2 | 1.49 | | 0.701 | 0.705 |
| 3 | 1.46 | 0.660 | 0.707 | 0.709 |
| 4 | 1.41 | 0.658 | 0.709 | 0.717 |
| 5 | 1.38 | 0.673 | 0.714 | 0.714 |
| 6 | 1.35 | 0.677 | 0.718 | 0.720 |
| 7 | 1.35 | 0.675 | 0.726 | 0.722 |
| 8 | 1.34 | 0.673 | 0.732 | 0.728 |
| 9 | 1.34 | 0.677 | 0.729 | |
| 10 | 1.32 | 0.670 | | |

natural condition of stability for the arc discharge. This occurs also in Fig. 5, in which Nottingham's values for the constants are applied to Malcolm and Simon's[3] data for a copper arc operated (1) normally with both electrodes hot, then (2) with cold anode and (3) with cold cathode. If this analysis be correct, the cooling of the cathode seems to have a more important effect on the discharge as a whole than does the cooling of the anode.

Altherthum and Ewest[13] conclude from their experiments that the anode exerts the more important effect over the entire discharge, for by preheating of the anode the striking and operating voltage of the arc was greatly reduced. The exact cause of such effects is not yet understood but may be important in explaining why the best results in arc welding are usually obtained when the welding rod is cathode. The above experiments also raise the question whether or not calorimetric determinations of the energy available at the arc electrodes give a true measure of conditions in the normal arc.

## Influence of the Anode Temperature

Hagenbach and Langbein[14] find that in normal arcs the anode is always boiling. When the atmosphere is non-oxidizing the cathode is heated less than the anode, but when both electrodes oxidize they reach the same temperature. Thus there arises the possibility that the effect of the anode temperature is shared by the cathode temperature which may be equal or nearly so. Experiments with arcs between totally different anode and cathode materials always reveal $n$ to be characteristic of the anode boiling or sublimation temperature.

Conditions at the anode give no indications of this far reaching effect of the anode temperature. The anode spot is thought to be surrounded by swarms of ions and electrons moving in a somewhat random motion. If at any moment the excess of electrons over positive ions reaching the anode is greater than the current in the arc circuit, a counteracting field sets in to repel the slower electrons; *vice versa*, and deficiency of electrons results in a strengthening of the field until the proper current is obtained. In this process the anode temperature does not seem to play any part, so that its effect must extend beyond the anode fall.

Beyond this region is the positive column which occupies the major portion of the arc stream length and exerts a considerable influence on the discharge characteristic as a whole. In the column intense ionization is taking place, always sufficient to replenish the large number of ions lost by recombination and diffusion. The ionization may be produced either thermionically or photoelectrically, and may be a combination of these methods. In the carbon arc the ionization is ascribed principally to high temperature,[15] and may therefore be controlled in some manner by the limiting temperature of the anode.

Nottingham[16] has found that when the arc anode and cathode are more or less equally volatile, the anode material usually becomes the "active" gas in the arc column. The temperature of this active gas could strongly influence its absorbtion properties, and therefore control the relative efficiency of the current conduction processes in this part of the arc. More evidence on this point will appear from energy considerations, which show that for high temperature arcs the conduction efficiency in the arc column is greatly improved.

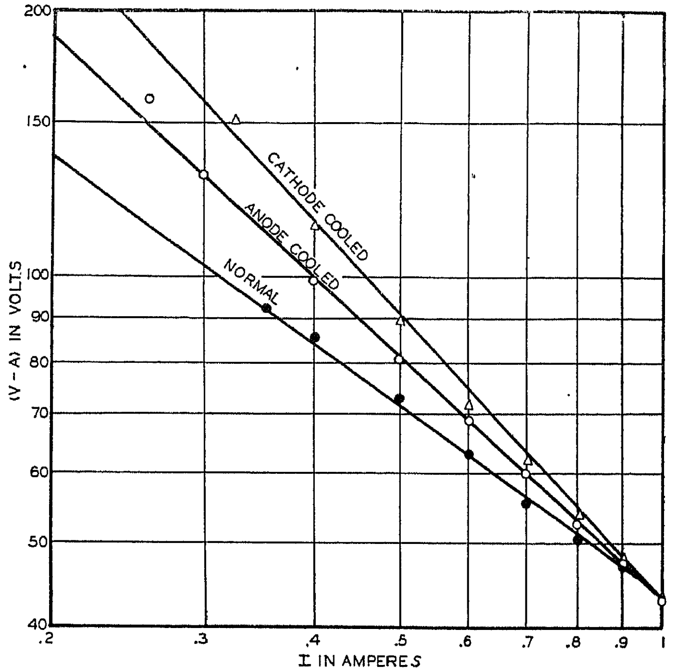

Fig. 5—Effect of Cooling the Electrodes—Copper Arc in Air

| | $A$ | $B$ | $n$ |
|---|---|---|---|
| Normal | 32 | 44 | 0.69 |
| Anode cooled | 40 | 43 | 0.88 |
| Cathode cooled | 50 | 43 | 0.98 |

(Arc length 4 mm)

While the function of the anode boiling point cannot be definitely explained, it can be stated that the important effect is the temperature and not any physical property associated with the boiling or sublimation point of the material. This temperature appears to impose an upper limit upon the activity and possibly the efficiency of certain processes in the arc stream. If in some manner the absorption and ionization properties of the active gas could be shown to be generally characteristic of this limiting temperature, it should prove to be a valuable starting point in explaining this important phenomenon. Any progress in this direction will be difficult, since conditions at the surface of the arc stream prevent direct observations or measurements of the interior.

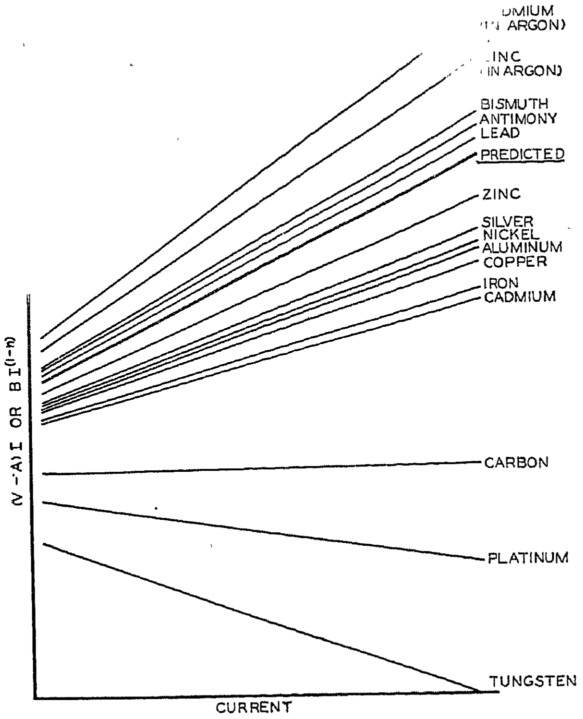

Fig. 6—Total Excess Energy Losses

## Energy Considerations

For very large currents theory and experiment show that the arc characteristic is approaching the form

$$V = A \qquad (6)$$

For infinite currents it is clear that the arc mechanism is *conducting the current at a minimum expenditure of energy per unit of current.* This minimum is determined by the lowest possible values of the following:

1. Anode and cathode falls.
2. Losses incident to conduction within the arc stream.
3. Losses external to the arc stream, such as radiated heat and light, and diffusion of ions.

For currents less than infinity items 1 and 3 are known to increase while 2 might increase a slight amount but probably remains almost constant. The total conduction efficiency of the arc therefore falls off as the currents diminish, for the expenditure of energy per unit current has grown larger. In other words, *the decrease in conduction efficiency makes it necessary to add to the right hand side of equation* (6) *the term* $B/I^n$, which becomes

$$V = A + B/I^n \qquad (4)$$

an equation known to represent the arc characteristic correctly. As the current enters to the $-n$ power, the losses vary inversely with the current, and this accounts for the *falling* characteristics of the volt-ampere curves and the so-called *negative resistance* of the electric arc.

The energy form of equation (4) may be written as

$$VI = AI + BI^{(1-n)} \qquad (8)$$

which involves the total amounts of energy instead of the energy per unit current. For any current, $AI$ is the *minimum conduction energy at "infinite current" conditions.* $BI^{(1-n)}$ or its equivalent $(V-A)I$ might be called the *"excess energy requirement" by virtue of the fact that conduction losses have increased as the currents are farther removed from infinite values.* These new concepts will be valuable. Their importance will become evident in some further considerations.

## Energy Division in the Arc

If the "excess energy losses" were entirely confined to item No. 3 (heat and light radiation, ionic diffusion) and were assumed to be linear functions of the cylindrical discharge surface, and if the arc current per unit cross section of that cylinder were constant, a value of the exponent $n$ might be predicted. From the geometry of the arc stream, and the above conditions

$$\frac{\text{total excess losses}}{\text{total arc current}} \propto \frac{\text{arc cyl. surface}}{\text{arc cross section}} \propto \frac{2\pi r}{\pi r^2} \propto \frac{2}{r}$$

Plotted logarithmically this would give a straight line relation with slope $(1-n) = 0.5$ or $n = -0.5$. Fig. 6 shows schematically how the actual "excess energy losses" of various arcs compare with this predicted value.

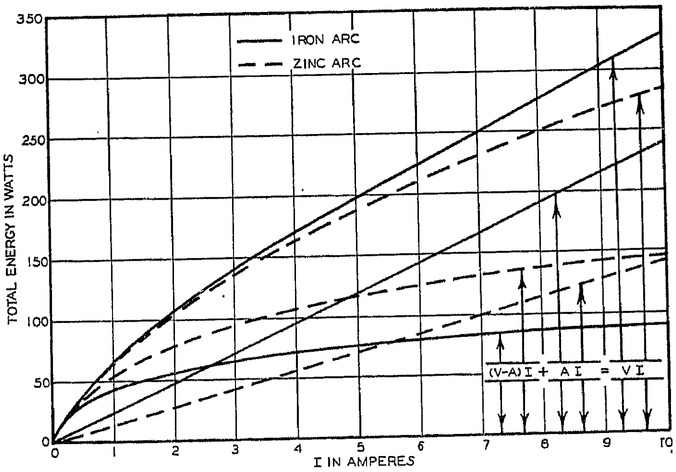

Fig. 7—Division of Energy in the Arc

The curves for lead, antimony and bismuth seem to correspond rather closely with this derived value of $n$. Actually the cadmium arc in argon, with $n = -0.275$, has been found to have a constant current density, at least over the 1—10 ampere region, thus fulfilling the geometrical conditions used in predicting a value of $n$. It is evident that theoretical predictions on such a basis are useful in giving a picture of the arc processes. When the ratio of losses in items 1, 2 and 3 becomes known and the factors regulating current density are evaluated, such predictions will be accurate and valuable.

Returning to the energy equation (8) it is possible to show how the "minimum energy for infinite current conditions" and the "excess energy" combine to represent the total energy input into the arc. In Fig. 7 such a division of energy is shown for zinc and iron arcs of 4 mm length. In comparing the currents at which the energy $BI^{(1-n)}$ is of the same magnitude as the $AI$ energy, this condition occurs at 2.5 amperes for the iron arc and at about 10 amperes for the zinc arc. This analogy may be carried to other arcs to demonstrate that the "excess energy requirement" falls off more rapidly as $n$ becomes larger, *i.e.*, as the anode temperature becomes higher, in the normal arcs.

The same conclusion may be drawn from an examination of the energy expenditures per unit current as implied in equation (4). A plot of $B/I^n$ *vs.* $I$ will have exactly the shape of the voltampere characteristics displaced a distance $A$ above the current axis. (Incidentally, all our tests of log $(V - A)$ *vs.* log $I$ as in Figs. 1, 2, 4 and 5 deal only with this "excess energy" and the exponential rate at which it varies with current.) In Figs. 8A and 8B such relations are given, both in logarithmic and rectangular coordinate plots, for a large number of arcs of 4 mm length. The rapidity with which the curves approach zero is seen to depend upon $n$, and therefore upon the anode temperature, indicating that high temperature arcs more rapidly approach the "infinite current" conditions and are consequently the most efficient on this score.

## The Arc Column

In accounting for the heat, light and ion losses which constitute the larger portion of the "excess energy" requirement, the size and conditions at the surface of the arc column seem more important than the phenomena within the column. In setting up the simple conditions for predicting a value of $n$, the current density was assumed independent of the current and constant over the arc cross section, as actually exists for the arc between cadmium electrodes in argon. A more exact survey of conditions requires that two additional items be considered.

1. The cumulative magnetic field of the conducted current is tending to concentrate the discharge about a longitudinal axis in its center. This is called the "pinch effect." It was fully described by Northrup[17] and was used by Barlow[18] in explaining why the arc did not spread out as the glow and other types of discharges do. The physical picture is given in Fig. 9 where the magnetic intensity curve is superimposed upon a cross section of the discharge column. The cumulative magnetic field $\beta$ creates a barrier just at the edge of the arc stream, and exerts its greatest inward pressure on the ions at this point.

2. The high temperature inside the arc discharge exerts a diffusion pressure opposing the concentrating effect of the magnetic field. Equilibrium between these opposing forces establishes the position of the magnetic barrier and surface of the discharge stream in relation to the central current axis.

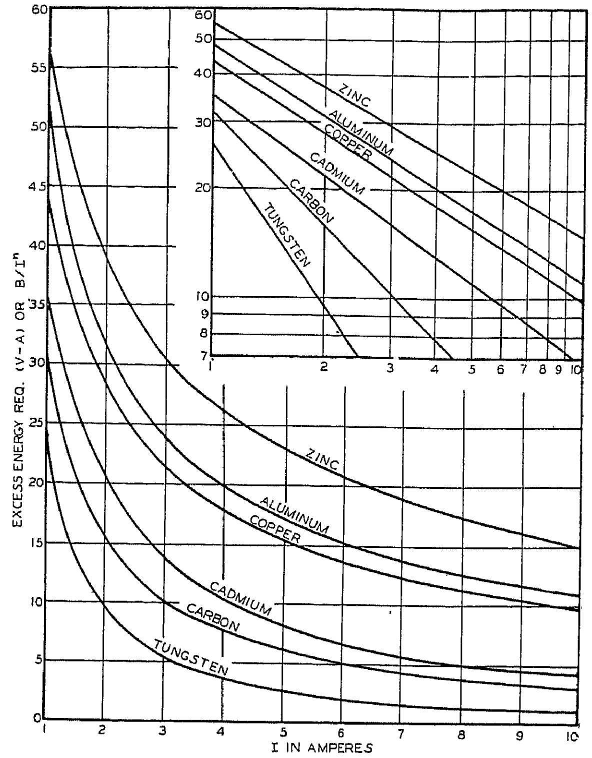

Fig. 8A Excess Energy Loss per Unit Current

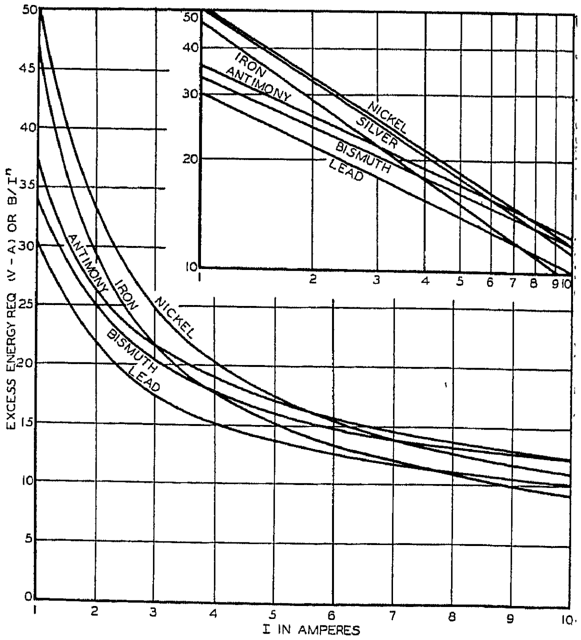

Fig. 8B—Excess Energy Loss per Unit Current

The logical deduction is that for high temperature arcs the positive column is somewhat larger in cross section than for low temperature arcs carrying the same current. Actual observations have shown this to be the case for copper, carbon and tungsten arcs in air. The relative enlargement is not very great, but the current density does decrease with temperature increase, in agreement with the above items.

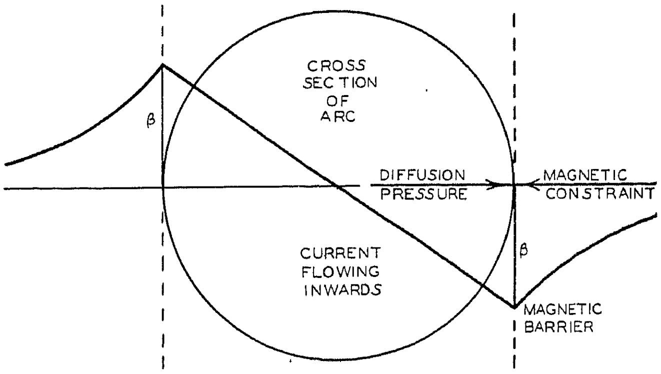

Fig. 9—Physical Conditions at the Arc Surface

If the high temperature arcs have *greater surface area*, then their "excess energy" losses might be *greater* than for low temperature arcs. But other considerations show that the "excess energy" losses are *less* than for low temperature arcs, a paradoxical state of affairs. Some interesting experiments on light emitted from the arc column suggest an explanation.

Nottingham[19] has measured the light per unit volume emitted from the arc. When plotted against current, as given in Fig. 10, the curves are seen to approach a "saturation value" in the order of increasing temperature—cadmium (in argon), copper, carbon and tungsten in air. The efficiency of the high temperatures seems to *limit the depth* from the arc surface through which the light and other radiation escapes, so that in spite of the increased surface areas the high temperature arcs are still more efficient than the low temperature arcs. Saturation of the emitted light per unit volume might then be thought to occur when there is some portion of the discharge which no longer contributes to this emission.

## Arc Extinction

As the term $B/I^n$ is a measure of the *rate of energy removal* from the discharge, it could play an important part in arc extinction. The most difficult arcs to extinguish would be those of high efficiency (low values of $B/I^n$). The increase of $B$ with arc length helps to explain why long arcs are more easily extinguished than short arcs, a basic principle employed in most circuit interrupters. The vanishingly small value of $B/I^n$ for very heavy currents allows an insignificant portion of the energy to be dissipated, and gives some idea of the difficulties in interrupting such circuits.

On the basis of these suggestions the contacting metals should be a matter of some importance in successfully interrupting a circuit. Since arcs between metals of low melting point show the greatest rate of energy dissipation, such metals should help to extinguish the arcs more quickly. Some recent experiments by Browne[20] show that this is not the case. The results of his tests in Fig. 11 prove that the arcs between high melting point metals are most easily extinguished. The fundamental differences between a-c arcs as used by Browne and d-c arcs as previously considered in this discussion removes this apparent contradiction.

While Fig. 9 is probably a correct physical picture of conditions in a d-c arc, it is only momentarily applicable to a-c arcs. In every cycle the magnetic barrier twice drops from a maximum through zero to a maximum in the reverse direction. In these 120 intervals each second when the magnetic and electric fields are removed, the ions can freely diffuse out of the arc stream *at a rate depending upon their temperature*. Of course there are other pertinent features involved in the exact theory of arc extinction, but this discussion helps to remove an apparent contradiction between theory and experiment.

## Arc Welding

Very few physical measurements have ever been made on heavy current arcs of the type used in arc welding, so that most of our concepts have been carried over from the smaller arcs studied in the laboratory. Doan[21] has set up the conditions of energy balance at the cathode of a welding arc, calculating the heat sources as indicated by the contemporary physical theories of the mercury and tungsten arcs. When applied to iron arcs of 150 amperes, theoretical calculations account for only half of the energy disbursed at

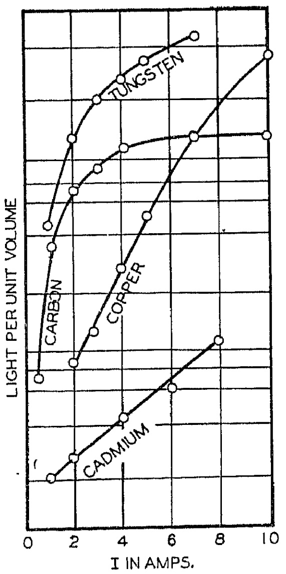

Fig. 10—Light Saturation Curves; Scale Not the Same for all Arcs

the cathode. While the constants of the iron arc have never been accurately determined, corrected values might bring the calculations into somewhat better agreement but would hardly make up the existing deficit.

As Doan has suggested, the greatest source of error probably lies in neglecting the heat of condensation of incoming positive ions. In low current arcs of the mercury and tungsten type this heat source is vanishingly small, but for heavy current arcs it may be considerable if the following reasoning is correct.

The heat, light and ionic diffusion losses from the arc column may be thought to come from a cylindrical layer rather than a surface. This seems consistent with the light per unit volume curves for low current arcs which show saturation as soon as a portion of the discharge along the central axis no longer contributes to the outside losses. In high current arcs this non-radiating, high efficiency portion becomes increasingly greater. (The intense heat and light often accompanying such arcs are believed to come principally from hot or burning vapors given off by the electrodes. The flaming arcs are notable examples.) All these losses in the outer layer are compensated by energy derived from the electric field which assumes a value commensurate with these losses. If the equipotential surfaces of this field are parallel planes at right angles to the arc stream, then the innermost non-radiating portions will derive an excess of energy above that which is needed for the ordinary ionization processes. This extra energy, since it results from a directed field, would seem to have a directed temperature effect enabling the current carriers eventually to contribute this energy as heat to the electrodes. The positive ions of the arc stream might thus reach the cathode in larger numbers than are now suspected, and their heat of condensation would be a large item.

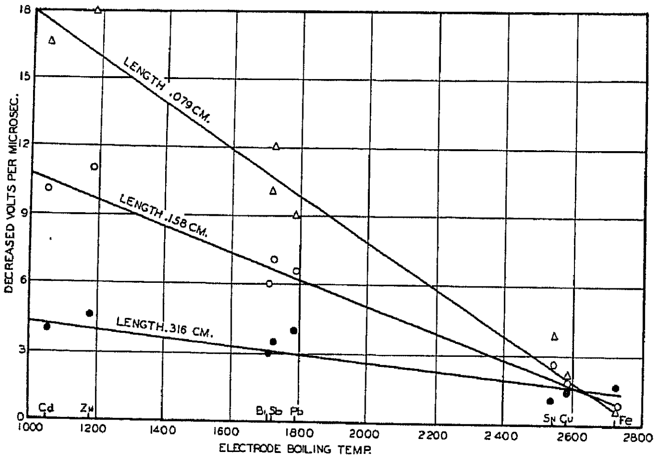

Fig. 11—Rate of Voltage Decrease for Arc Extinction. From Brownes 300-Amp, 450-Volt A-C Arc Experiments

Such assumptions do not violate our physical picture of small current arcs, and yet provide an additional heat source which is certainly needed to satisfy the energy equilibrium conditions at the cathode of heavy current arcs. Furthermore they are in good agreement with probe measurements which show that as the probe sweeps through the inner portions of the arc stream the *positive ion current per unit length of the probe* increases rapidly with the arc current.

A logical deduction is that these positive ion currents help to explain the very rapid cathode deposition which results in the arcs used in "hot welding." If the factor involving the energy from the incoming ions were zero, the cathode energy would very nearly be limited to a linear increase with welding current or cathode fall. Table II[22] shows that this cannot be true, since the cathode deposition increases much more rapidly than the arc current. As the "hot welding" arcs are long in comparison with arcs of the older process, the positive ions can acquire considerable extra energy (in falling through the large non-radiating portions of the arc stream) to be delivered at the cathode. It is probably along these lines that the success of "hot welding" and other improvements in the welding process can be explained.

TABLE II—TYPICAL CURRENT AND CATHODE DEPOSITION OF "HOT WELDING" ARC

| Arc current amperes | Cathode deposition pounds per hour |
|---|---|
| 300 | 5.0 |
| 350 | 7.5 |
| 400 | 10.0 |
| 500 | 15.0 |
| 550 | 20.0 |
| 600 | 25.0 |
| 700 | 30.0 |
| 750 | 35.0 |

## General Conclusions

The following concepts of the arc discharge phenomena are indicated from these new studies:

1. There is a "minimum energy" requirement of $A$ watts per unit current in the arc conduction process, implying (a) a minimum of potential in drawing the charged particles into or out of the electrodes, and (b) the highest efficiency in conveying these charges through the arc stream. These conditions actually exist when the arc current approaches infinite values.

2. There is an "excess energy" requirement by virtue of the fact that the conduction efficiency decreases as the currents are farther removed from infinite values. Decreasing currents cause an increase in (1) the combined electrode falls, and (2) the surface losses per unit volume of the discharge column, which collectively represent the "excess energy" requirement of $B/I^n$ watts per unit current.

3. These energy requirements per unit current combine to represent the voltampere characteristics. The functioning of the "excess energy" term $B/I^n$ *explains* the falling slope of the characteristics, and the so-called

"negative" resistance of the electric arc. In other words, the net efficiency of the arc increases with current.

4. The current exponent $n$ indicates the rate at which the arcs approach "infinite current" conditions. As $n$ is proportional to the anode temperature, this temperature appears to influence the ionization and absorption properties of the positive column, and therefore regulates the efficiency of these processes. On this basis, the high temperature arcs are the most efficient.

5. The largest portion of the "excess energy" losses probably result from heat and light radiation and ionic diffusion from the arc stream. There is evidence that this radiation and diffusion come from a cylindrical layer of the arc stream whose depth is inversely proportional to the gas temperature, so that in spite of the slightly increased surface of high temperature arcs their efficiency is still higher than for low temperature arcs.

6. In high current arcs there are considerable portions of the discharge which do not contribute to the surface losses. In falling through the electric field the ions in this non-radiating, high efficiency portion may acquire an extra energy over those near the surface. Under the effect of the directed field they would contribute this extra energy as heat to the electrodes. Energy equilibrium conditions at the welding arc cathode make such a suggestion plausible.

These studies tend to unify some general conclusions from seemingly unrelated experiments in giving a more complete physical picture of the arc discharge. Certain concepts should be useful in bringing theory and practise into better agreement, and enabling proper application of the arc in commercial problems. Above all, the need for correlated measurements on the arc discharge is emphasized.

The author is particularly grateful to Professor Doan of Lehigh University under whose guidance and direction these studies have been carried out, for his interest and encouragement in the work; to Professor Hertz for laboratory facilities at the Charlottenburg Technishche Hochschule, and to Engineering Foundation whose support made these studies possible.

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## Discussion

**A. R. Miller:** In this paper Mr. Myer starts with an equation which has withstood the criticism of students of arc theory for some time, and attempts an explanation of the equation starting from an energy point of view. This is somewhat analogous to a practise among electrical engineers when discussing circuit problems such as transient conditions, whereby energy is assumed to be dissipated or transferred, in contradistinction to speaking of these things in terms of voltages. However, there seems to be a fundamentally logical procedure in this instance when discussing the arc phenomena, in that it attaches some meaning to the various terms of the equation. The equation referred to ($V = A + BI^{-n}$) and its predecessors seemed to have been devised as an equation to fit a curve plotted from experimental data, without any recourse to reason. This sufficed for many engineering purposes however. Since then many have tried to explain the various terms (or even other forms of equations for the same phenomena) in various ways and by various means.

Myer finds discrepancies in his point of view, in much the same way as others have found shortcomings in theirs.

Various theories are in existence in regard to arc phenomena. Thus some[1] explain a part of it on the assumption of thermionic forces, which may quite agree with certain conditions, and which certainly play a part in arc theory. Others[2] seem to think that the electric field has considerable to do with it; in fact under certain conditions, as in vacuum tubes, it may be the important factor. In any case it can hardly be doubted to be a combination of the two. Other mechanism must also be considered, as for instance the surrounding medium. All of these factors are taken care of in a collective way in the "energy" method of approach. By any route the explanation is a difficult one hampered by many factors to be controlled.

It seems that one line of attack which has as yet received little attention, but which might supply other lines of thought is the phenomena which occurs in very short time intervals upon the establishment of the arc, or in its variation. There is available at present the cathode ray oscillograph which enables the measurement of currents and voltages of very short time intervals and might be useful in verifying some of the ionization theories supposed to play a role in arc-phenomena. Such studies can be carried out with the equipment in many electrical engineering laboratories.

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[1] Compton.
[2] Langmuir.

# Transients In Arc Welding Generators
## With Experimental Verification

BY A. R. MILLER*
Associate, A.I.E.E.

***Synopsis.***—*This paper gives a mathematical analysis of armature and field transients in d-c generators of the type used in arc welding. The analysis is reduced to the simplest form, and is exact, under the premises given. Armature and field currents only are treated, and comparisons between calculated and experimental graphs are shown.*

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DURING the last few years a great deal of study has been given to the design of d-c arc welding machines with a view of obtaining more desirable characteristics under transient conditions. To this end several types of construction have been employed, as for example, the neutralized and transformer-coupled welders. The latter have been designed in several different ways, and the question of their electrical principles has been discussed. Recently tests have been made on a generator so connected, and an attempt was made to predict the important features of its operation under transient conditions. The results of such an investigation have been embodied in this paper.

The transient solutions of currents in d-c machines have been made before, but these have mainly considered the theoretical side only, and have dealt almost wholly with currents in the armature and field circuits. With the addition of transformer connections between the field and armature circuits, and also because certain characteristics are desired when the current changes from one value to another as in welding, more complete solutions are desirable.

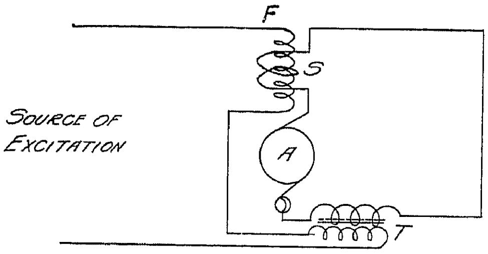

FIG. 1—WIRING DIAGRAM

$S$ = series field
$F$ = shunt field
$A$ = armature
$T$ = transformer

ASSUMPTIONS USED IN MAKING CALCULATIONS

When applying electrical circuit theory to arc welding machines, certain simplifying assumptions can usually be made. These are as follows:

1. The excitation of the field is from a constant voltage source. While there are exceptions to this, it is for almost all cases quite general. The machine for which the oscillograms are shown and for which the calculations were made had constant excitation from a battery, with a view towards simplifying the calculations.

2. The magnetic circuit of the machine had small eddy current effects, and magnetic saturation did not exist. For present arc welding generators these assumptions are quite legitimate, since the magnetic circuits are usually laminated, and the voltages under operation are but a fraction of the maximum possible voltage.

3. The series and shunt fields are differentially connected, magnetically, to each other.

4. Rotational speed of machine constant under all loads.

A diagrammatic sketch of a d-c generator with a transformer connection between armature and field circuit is shown in Fig. 1.

INTERPRETATION OF SOLUTIONS

It might be of advantage to show the method of obtaining the graphs, which are shown in comparison with the oscillograms, in that it may be helpful when interpreting the meaning of several factors which enter into the calculation of the currents.

The solution for the armature current, taking as an example a machine without reactor or transformer coupling between field and armature circuits, is given by the following equation.

$$i_1 = 75 + 660\, \epsilon^{-49.8t} - 735\, \epsilon^{-101.2t} \qquad (8)$$

The plotting can be done most readily by drawing the three component parts, and then adding graphically as shown in Fig. 2. For example, values of time required to give the exponential factor of 75, 50, 25 and 5 per cent of the coefficient can be obtained and each curve plotted, then added. By so doing, it is seen that the recovery to steady state is dependent upon the term having the smaller exponential factor. The amplitude of the component also has its effect, of course. The time at which the currents are at a maximum from the normal or steady state condition is largely determined by the term having the larger exponential constant, and consequently the amount of overshooting which will occur. Hence, from the tabulated values of the coefficients and exponential factors for the various components, it is quite possible to approximate very closely the amount of overshooting and the time to recover to any percentage of normal value, without the more laborious method of plotting out the equation.

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*Asst. Professor, Elec. Engg., Lehigh University.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., Jan. 23-27, 1933.*

## Experimental Verification of Solutions

Certain typical oscillograms for which solutions have been obtained are shown in Figs. 3, 4, 5 and 6. Equation (7) (Appendix A) has several typical solutions, depending upon the magnitude and sign of the quantity under the radical.

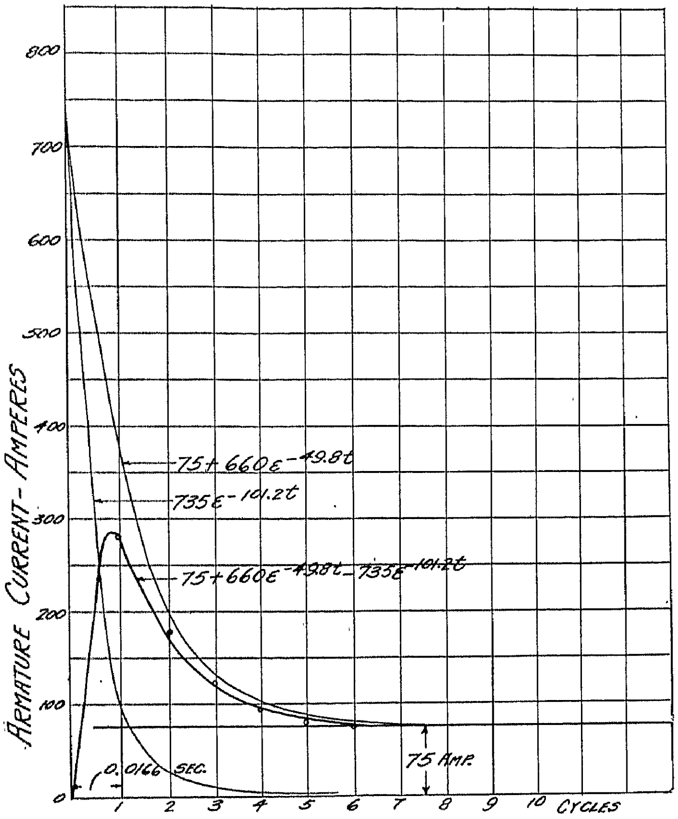


Fig. 2—Component Parts of a Solution

Calculated graph of armature current for Fig. 3
° Values from oscillogram—Fig. 3

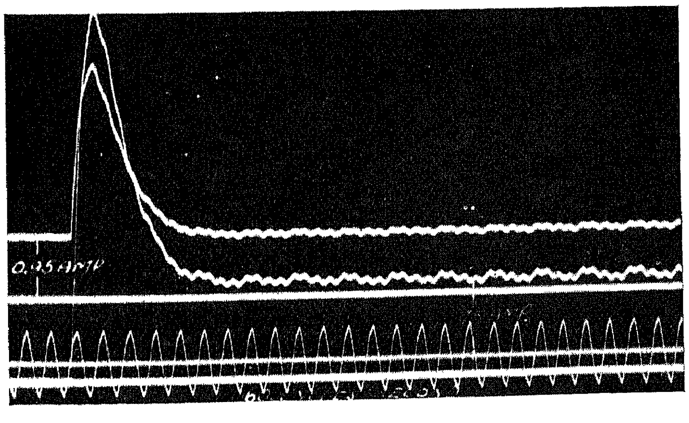
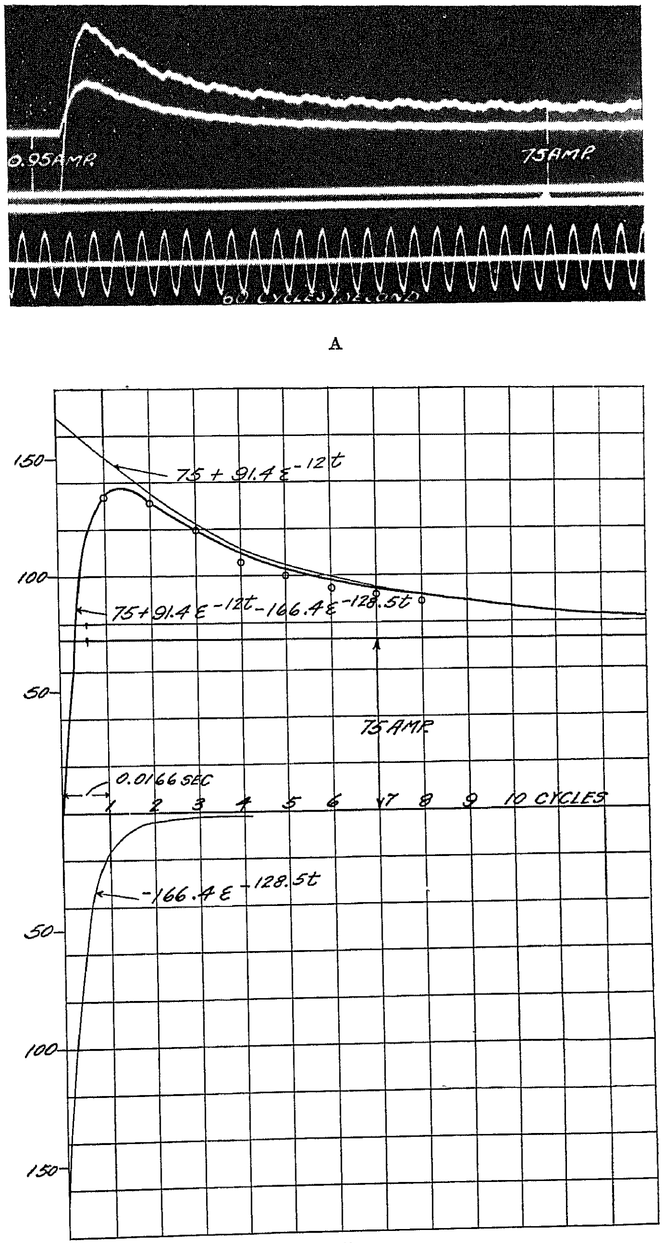


Fig. 3—Armature and Field Currents in a D-C Generator—No External Inductance

Fig. 3 was obtained under a condition which gave to this radical a positive value, the solution in this instance becoming, for the armature current (Appendix A)

$$i = 75 + 660\,\epsilon^{-49.8t} - 735\,\epsilon^{-101.2t} \qquad (9)$$

A plot of this equation is shown in Fig. 2. There results an overshooting of the steady-state value of both field and armature currents. This condition will obtain for all values which the radical may have, except for one case to be mentioned later. As the value of this radical, while remaining real, is decreased, the two roots approach each other in value, since one is the sum and the other the difference of the two terms.



A

B

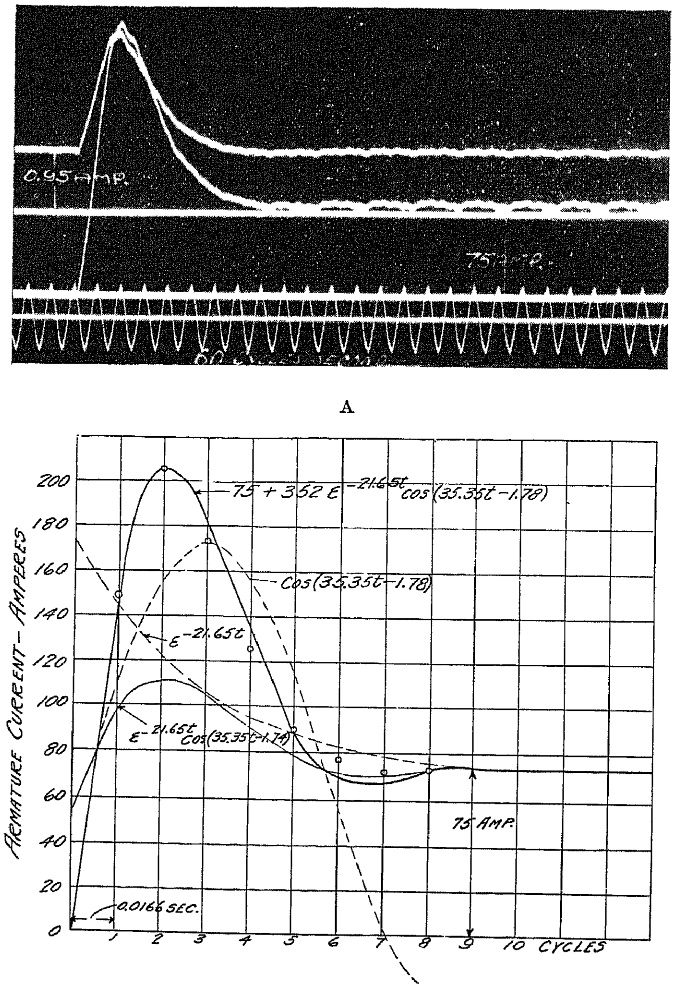
Fig. 4—Armature and Field Currents in a D-C Generator With Shunt Field Inductance Added Externally

A. Oscillogram of armature and field current
B. Calculated graph of armature current
° Values from oscillograms

There are of course particular values for which the radical is zero, and only one distinct root then results. This is sometimes said to be a case of equal roots. As this condition is approached, the coefficients of the transient terms become larger in magnitude, but the difference will always be such as to make the current overshoot the normal value, and will have a definite value.

Experimental verification of the above discussion is obtained in Figs. 3 and 4. In Fig. 3 the radical contains two terms which are relatively alike in value, while in Fig. 4 these roots are considerably separated. The latter condition was obtained by adding inductance to the field circuit. The equation for the armature current in Fig. 4 is

$$i_1 = 75 + 73\,\epsilon^{-9.9t} - 143\,\epsilon^{-189.5t} \qquad \textbf{(10)}$$



A

B

FIG. 5—ARMATURE AND FIELD CURRENTS IN A D-C GENERATOR WITH INDUCTANCE ADDED TO ARMATURE CIRCUIT

A. Oscillogram of armature and field current
B. Calculated graph of armature current
° Values from oscillogram

The plot of the component parts of equation (8) as shown in Fig. 2 has for the component terms values much in excess of those in Fig. 4B.

If the value under the radical is made negative, as for example by increasing the negative term under the radical, the roots become imaginary, and the solution is oscillatory in so far as its form is concerned. The oscillogram shown in Fig. 5A was taken under conditions such that there results negative roots, brought about by increasing the inductance of the armature circuit. The equation for the armature current is (see Appendix A):

$$i_1 = 75 + 336\,\epsilon^{-21.7t}\cos(33.3t - 1.78) \qquad \textbf{(11)}$$

The terms with imaginary coefficients have been converted to a cosine function. Due to the large decrement in the coefficient of the cosine term, and also to its low frequency (5.14 cycles per second), the oscillogram and calculated current shows little which would indicate that such a condition exists.

It can be noticed on the oscillogram that the current curve slightly touches the line below just before the current settles to a final value. This is perhaps due to the oscillatory component.

An interesting feature is the range of values which the inductance of the armature circuit may have, over which an oscillatory solution exists. By referring to equation (7) (Appendix A), it is noted that the radical will contain a negative number, if the second term is larger than the first; the roots are then complex, and give rise to the oscillatory solution. Equating the terms under the radical to zero,

$$(L_1R_2 + R_1L_2 + K_{11}L_2 - K_{12}M)^2 - 4\,(L_1L_2 - M^2)\,(R_1R_2 + K_{11}R_2) = 0$$

and assuming values for all constants except $L_1$, there will be found two values for $L_1$ which satisfy this equation. Taking the constants as given for the machine alone, the case of equal roots exists for a value of armature inductance equal to

$$L_1 = 0.0056 \text{ or } 0.272 \text{ henry.}$$

Any value of $L_1$ within this range gives complex roots, and hence an oscillatory solution. Values lower than 0.0056 henry or greater than 0.272 henry will have two real roots. Thus in the oscillogram cited above, when $L_1 = 0.0045$ henry (Fig. 3) there results two real roots; when $L_1 = 0.0075$ henry (Fig. 5) there are complex roots, the latter being in the range of values given above.

From the preceding discussion, it is evident that the case of equal roots, so called, is merely a borderline between solutions having real and imaginary roots, and for quite a large range of values the actual current variation obtained is quite similar. The values of armature inductance used in these tests were quite close to the lower limit, and give graphs of current which have similar characteristics. This is in agreement with what would be expected, as the inductance is gradually increased, as was done in this case, there would be only a gradual change in the magnitude and shape of the current as shown on an oscillogram.

The introduction of an interconnection between the armature and field circuits by means of a transformer gives some interesting results. In this manner it is possible, if the transformer is properly designed, to neutralize the effect of the mutual inductance between the series and shunt field coils within the machines by means of that in the transformer. Experimentally, complete neutralization was not obtained, but the mutual inductance was reduced from 0.3 henry to approximately 0.2 henry. An oscillogram of the armature and field current is shown in Fig. 6, and the calculated armature current in Fig. 7.

The most peculiar phenomena which exists in this case is the manner in which the two transient terms in the solution behave as the total mutual inductance is reduced towards zero. The two roots approach as a final value the roots which would be obtained for either circuit alone; at the same time the coefficient for the term having the root approaching that of the field circuit (for the field circuit alone) gradually reduces to zero. In Table I is given the exponential factors and the corresponding coefficients.

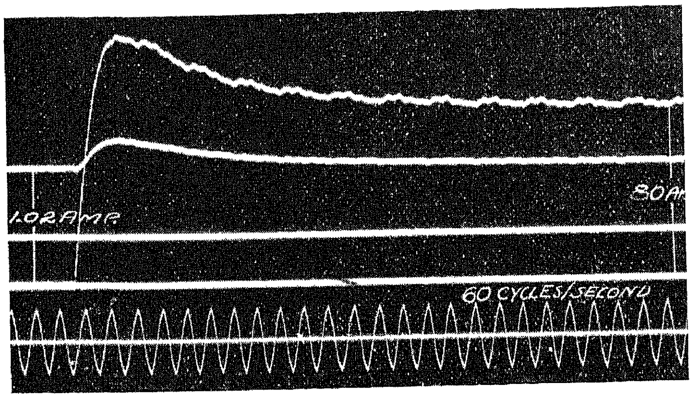


FIG. 6—ARMATURE AND FIELD CURRENTS IN A D-C GENERATOR WITH TRANSFORMER BETWEEN FIELD AND ARMATURE CIRCUIT

TABLE I

| $M$ | $a_1$ | $A_1$ | $a_2$ | $A_2$ | $I$ |
|---|---|---|---|---|---|
| 0.2 | −7.40 | 42.8 | − 78.7 | 117.8 | 75 |
| 0.1 | −5.84 | 16.0 | − 89.5 | 91 | 75 |
| 0.05 | −5.32 | 7.5 | − 96.5 | 82.5 | 75 |
| 0 | −4.86 | 0 | −104.5 | 75 | 75 |
| −0.1 | −4.07 | −12.0 | −118.5 | 63 | 75 |

Solution: $i_1 = I + A_1 \epsilon^{a_1 t} - A_2 \epsilon^{a_2 t}$

Mathematically, equation (7) (with $M = 0$) reduces to

$$\frac{-L_1R_2 + (R_1 + K_{11})L_2 \pm \sqrt{[L_1R_2 - (R_1 + K_{11})L_2]^2}}{2\,L_1L_2}$$

which gives, in the limit,

$$-\frac{2\,L_1R_2}{2\,L_1L_2} \text{ or } -\frac{R_2}{L_2} \text{ as one root, and}$$

$$-\frac{2\,(R_2 + K_{11})L_{12}}{2\,L_1L_2} = -\frac{(R_1 + K_{11})}{L_1} \text{ as the other.}$$

Fig. 7 has a mathematical plot for the condition of $M = 0$, by way of comparison.

The physical interpretation of this case is not difficult to understand. With no mutual impedance between the circuits, one current cannot react upon the other; in other words, the transient current acts as if in a circuit far removed under these conditions.

If the mutual inductance of the transformer is larger than that of the machine, the above solutions still hold, $M$ becoming negative in value. One solution under these assumptions for armature currents is shown graphically in Fig. 7. The rate of rise in the armature current is much reduced, and a plot of the field current would under these conditions show a decrease instead of an increase of current just after short circuit, as would be expected.

The above case of zero mutual inductance suggests the nature of the two exponential factors which are contained in the solution of the currents. The larger exponential factor appears to be due to the armature circuit, as modified by the field circuit; the smaller factor in turn due to the field, as modified by the armature circuit.

By reference to Table I the nature of the variation of the exponential factors and the corresponding coefficients can be observed. $a_1$ is the exponential factor pertaining to the field circuit, and $A_1$ the coefficient of the corresponding transient term. As the mutual inductance is lowered the exponential factor decreases through the value for the field as an isolated circuit (− 4.86 for the conditions assumed) to still lower values. In the meantime the coefficient $A_1$ which largely determines the overshooting of the armature current, decreases to zero and becomes negative in value, prolonging the armature transient as can be seen in Fig. 7.

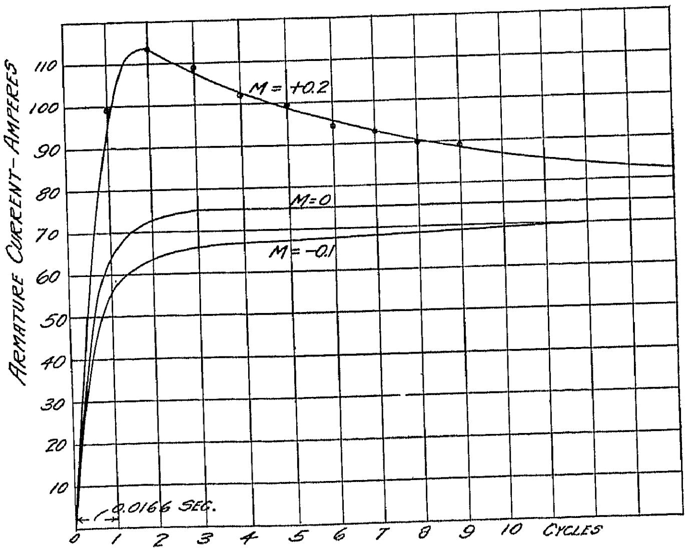


FIG. 7—ARMATURE AND FIELD CURRENTS WITH $M = 0$ AND $M = -0.1$

Upper curve—calculated graph for Fig. 6
° Values from oscillogram

The exponential factor $a_2$ which is that of the armature circuit as modified by the field, continually increases in value, while the corresponding coefficient decreases. The net effect is, compared to that of this term when $M$ is positive, to decrease the rate of increase of the armature transient current.

A comparison of the results obtained by inserting inductance in the armature circuit is shown in Fig. 8 below. These graphs were calculated under the assumption that all circuit constants except armature self-inductance remained fixed. The graphs for 0.0045 and 0.007 henry inductance are experimentally verified in Fig. 3 and Fig. 5.

If the value of the armature inductance is increased beyond the range of values giving complex roots (0.00563 henry to 0.272 henry) it is interesting to note that there is a considerable change in the nature of the solution for the armature current. For a value of $L_1 = 0.0045$ henry,

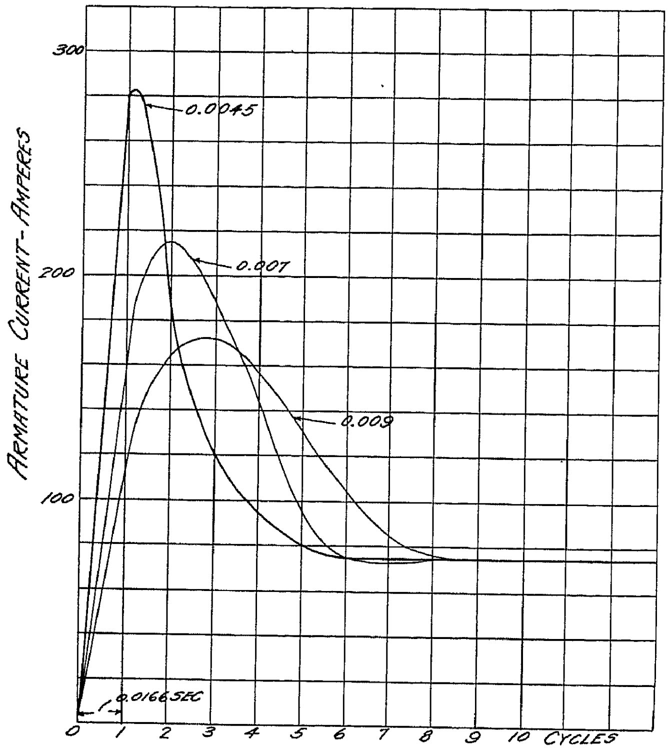


FIG. 8—EFFECT OF VARIATION OF ARMATURE CIRCUIT INDUCTANCE

$$i_1 = 75 + 660\,\epsilon^{-49.8t} - 735\,\epsilon^{-101.2t} \qquad (8)$$

Assuming $L_1 = 0.3$ henry, which is in the region of real roots again,

$$i_1 = 75 - 106\,\epsilon^{-3.5t} + 31\,\epsilon^{-6.28t} \qquad (15)$$

The order of the exponential factors have been kept the same in writing the two equations to make it easier to compare the coefficients. It will be noted the coefficients have changed order in relative magnitude, as well as in sign. That is, before entering the complex root region, the larger coefficient went with the larger exponential factor, and was negative in value; when leaving this region exactly the reverse conditions exist.

As the inductance is varied over the range of values giving oscillatory solutions, the frequency of the oscillations becomes less as higher values of inductance are used and the exponential factor becomes smaller in magnitude, as does the coefficient of the cosine term. That is, there is a less rapidly varying current for an armature transient, and it lasts over a longer interval of time.

Thus, with 0.0075 henry inductance in the armature the current is

$$i_1 = 75 + 336\,\epsilon^{-21.7t} \cos(33.3t - 1.78) \qquad (11)$$

and with 0.2 henry assumed, it is

$$i_1 = 75 - 90.7\,\epsilon^{-5.01t} \cos(2.915t - 0.6) \qquad (16)$$

## FIELD CURRENT

Only one solution for the field current is given. This matter is of minor importance as far as currents are concerned. In Fig. 9 a graph is plotted for the field current shown in the oscillogram in Fig. 3. The current in this instance is (equation (9), Appendix A)

$$i_2 = 0.96 + 8.73\,\epsilon^{-49.8t} - 8.73\,\epsilon^{-101.2t} \qquad (9)$$

The field current may become of importance in the calculation of voltages in various parts of the machine, but that matter, together with others, is reserved for a future paper.

In the oscillograms which are shown a considerable amount of superimposed ripples will be noted in the current. In some instances, as on the rapidly rising portion of the current graph, this has made the matter of scaling the oscillograms inaccurate. As far as possible an average value has been taken. The calibration of the films was obtained from the steady-state portion, which was read by a d-c ammeter during the tests. Hence, in using this portion, an average value of the ripple was assumed to be correct.

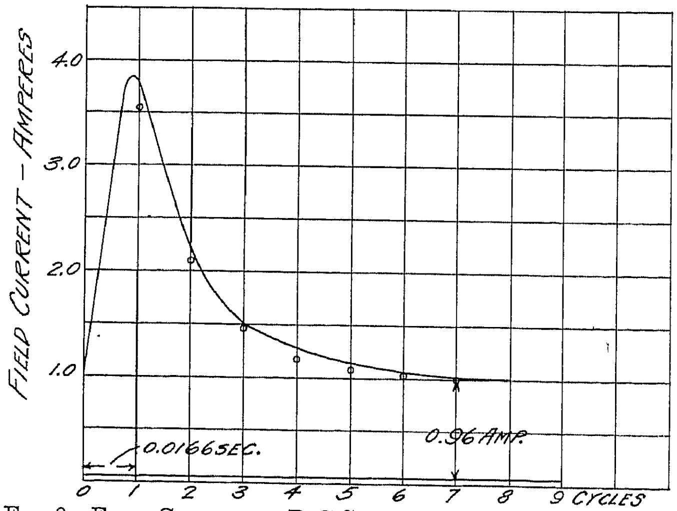


FIG. 9—FIELD CURRENT IN D-C GENERATOR WITH NO EXTERNAL FIELD OR ARMATURE INDUCTANCE

° Values from oscillogram

While the above tests were made on arc welding generators, the conclusion must not be drawn that the results represent typical conditions. The constants of the generators were changed in such a manner as would best demonstrate the possibility of making calculations for unique circuit conditions. As a matter of fact the machines as originally designed perform very satisfactorily under operating conditions.

The above investigation shows that it is possible, once the proper design constants are known, to predetermine the currents in an arc-welding generator due to circuit changes. It seems, on the basis of the above, that it should be possible to lay down without much difficulty a standard method of testing to determine the machine constants and a standard calculation schedule from which the most important points in the welder characteristics could be determined.

Acknowledgment is made of the assistance in the experimental work and the preparation of the material for this paper of Professor F. Creedy, Mr. E. C. Easton, and Mr. F. B. Lucas of the Electrical Engineering Department of Lehigh University.

## List of Symbols

$R_1$ = resistance of armature circuit.
$R_2$ = resistance of field circuit.
$L_1$ = self-inductance of armature circuit, including the armature winding, series field, and any reactor or other device which may be in that circuit.
$L_2$ = total self-inductance of the field circuit.
$M$ = $M_{12} = M_{21}$ = mutual inductance between the armature and field circuit. Saturation is assumed negligible.
$K_{12}$ = rotation voltage constant between shunt field current and voltage induced by the rotation of the armature in the magnetic field produced by the field current.
$K_{11}$ = rotational voltage constant for the series field current.
$E$ = open circuit (or induced voltage) produced by the field current prior to a transient condition in the armature.
$p$ = $d/dt$.
$t$ = time in seconds.

## Appendix A

### ARMATURE AND FIELD CURRENTS

During transient conditions in a compound wound generator, there are voltages due to the following causes:

1. Rotational voltage due to field current.
2. Rotational voltage due to armature current in series field.
3. Voltages in either circuit by virtue of the mutual inductance between the armature and field circuits due to the variation in the other.
4. Voltages in each circuit produced by the self-inductance of each circuit from the change of current in that circuit.
5. Voltages due to resistances in either circuit.

Fig. 10 shows a diagrammatic sketch of the equivalent circuit of a differentially connected arc-welding generator.

Assuming the positive directions of currents to be as shown, then

$$E - (R_1 + K_{11} + L_1 p)\, i_1 + (K_{12} + Mp)\, i_2 = 0 \qquad (1)$$

for the armature circuit.

This is a statement of the condition for voltage relationships in a closed armature circuit. $E$ is the voltage produced in the armature circuit by the field current prior to short-circuit, and is assumed constant. Consequently $i_2$ is the change in value from that initially existing in the field circuit.

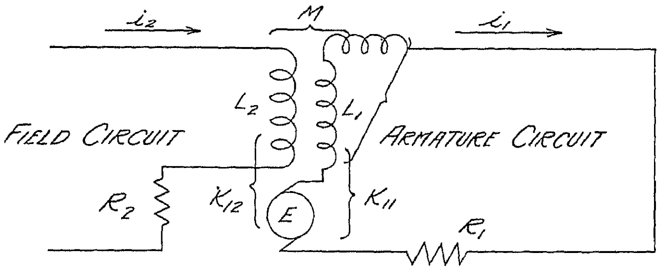


FIG. 10—EQUIVALENT CIRCUIT OF A D-C GENERATOR WITH SEPARATELY EXCITED FIELD

When the armature current is flowing in a positive direction, the series field flux in a differential wound compound machine opposes the main field flux; hence the minus sign with $K_{11}$. Any increase in a positive direction of the field current produces a voltage in the same direction in the armature circuit as the voltage $E$, which gives to $K_{12}$ a plus sign. Also, any positive rate of change of the field current will produce a voltage in the armature circuit in the direction of $E$; that is, in the positive direction of $i_1$. See Fig. 11. In other words, an increase in $\phi_2$ will be compensated by an increase of $\phi_1$ in the direction shown. This would require an induced voltage producing $i_2$, which is in a positive direction.

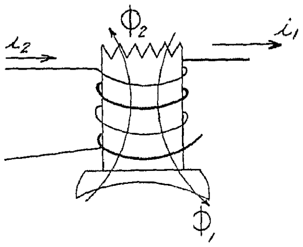


FIG. 11—RELATIVE DIRECTIONS OF ARMATURE AND FIELD CURRENTS ABOUT FIELD POLE

The differential equation for the field circuit is,

$$Mpi_1 - (R_2 + L_2 p)\, i_2 = 0 \qquad (2)$$

These equations solved simultaneously for $i_1$ and $i_2$ give the following results.

$$i_1 = \frac{(R_2 + L_2 p)\, E}{(R_1 + K_{11} + L_1 p)\,(R_2 + L_2 p) - (K_{12} + M\,p)\,(Mp)} \qquad (3)$$

$$i_2 = \frac{Mp\, E}{(R_1 + K_{11} + L_1 p)\,(R_2 + L_2 p) - (K_{12} + M\,p)\,(Mp)} \qquad (4)$$

It must be remembered that the latter gives only the change in value of the field current from that required to produce $E$ on open circuit; in other words, from the field current prior to short circuit.

The denominator in equations (3) and (4) above, when multiplied out and terms collected according to the powers of $p$ is

$$(L_1L_2 - M^2)\,p^2 + (L_1R_2 + R_1L_2 + K_{11}L_2 - K_{12}M)\,p + (R_1R_2 + K_{11}R_2) \qquad (5)$$

In this particular study operational calculus can be used to advantage. Of the various methods of solutions, the expansion theorem is most adaptable. The solution, by this means, becomes

$$i = \left[ \frac{Y_{(o)}}{Z_{(o)}} + \sum_{p = p_1}^{p = p_n} \frac{Y_{(p)}\,\epsilon^{pt}}{Z_{(p)}'\,p} \right] E \qquad (6)$$

In this equation $Y_{(p)}$ is the numerator and $Z_{(p)}$ the denominator of the operational solution, as a function of $p$. $Z_{(p)}'$ is the function obtained by differentiating $Z_{(p)}$ with respect to $p$. $p_1 \ldots p_n$ are the roots of $Z_{(p)}$. $Z_{(p)}$ for the armature and field currents is given by equation (5) above.

Accordingly $\dfrac{Y_{(o)}}{Z_{(o)}} = \dfrac{E}{R_1 + K_{11}}$ for the armature current, and 0 for the field circuit.

Also

$$p_{1,2} = \frac{-(L_1R_2 + R_1L_2 + K_{11}L_2 - K_{12}M) \pm \sqrt{(L_1R_2 + R_1L_2 + K_{11}L_2 - K_{12}M)^2 - 4\,(L_1L_2 - M^2)\,(R_1R_2 + K_{11}R_2)}}{2\,(L_1L_2 - M^2)} \qquad (7)$$

For a particular generator, without transformer or armature circuit reactor, $R_1 + K_{11} = 0.70$; $K_{12} = 55$; $L_1 = 0.0045$; $L_2 = 27.9$; $R_2 = 260$; $M = 0.3$; $E = 53$; $I_2 = 0.96$.

The solution is, for the armature current

$$i_1 = 75 + 660\,\epsilon^{-49.8t} - 735\,\epsilon^{-101.2t} \qquad (8)$$

and the field current under the same conditions, when the intital field current is added is

$$i_2 = 0.96 + 8.73\,\epsilon^{-49.8t} - 8.73\,\epsilon^{-101.2t} \qquad (9)$$

If the field circuit inductance is increased to 50 henrys,

$$i_1 = 75 + 73\,\epsilon^{-9.9t} - 143\,\epsilon^{-189.5t} \qquad (10)$$

When the armature circuit has its inductance increased to $L_1 = 0.0075$ henrys, and the field circuit inductance restored to the first value, then

$$i_1 = 75 + 336\,\epsilon^{-21.7t} \cos(33.3t - 1.78) \qquad (11)$$

If the transformer is added

$L_1 = 0.006$; $L_2 = 45.0$; $R_2 = 243$; $M = 0.2$

The equation for armature current under these conditions is given by

$$i_1 = 75 - 166.4\,\epsilon^{-128.5t} + 91.4\,\epsilon^{-12.0t} \qquad (12)$$

The first cases, given by equations (8), (9) and (10), are cases of real roots; the second, given by equation (11), a condition giving complex roots; and the latter, equation (12), an approach to a solution having two roots, only one of which will have a coefficient in the limit, when $M = 0$.

## Appendix B

### SUDDEN CHANGE IN THE ARMATURE CIRCUIT RESISTANCE

During the process of welding there is the equivalent of a change in the resistance of the armature circuit, when the distance between the electrodes is changed, or when the electrodes come into contact with each other. Fig. 12 shows a diagrammatic sketch of a d-c generator with the resistance in two sections in the armature, one of which can be short-circuited by a switch. Closing the switch is equivalent to removing the resistance from the armature circuit. The initial condition, that is, prior to closing the switch, is that there exists a certain current in the armature circuit, as determined by the condition just prior to removing the resistance.

The operational processes used in the solution in Appendix A assume no current as an initial condition. However, in a circuit having linear voltage-current relationships as the one considered, solutions can be superimposed.

As far as the circuit is concerned, instead of the short-circuiting switch, suppose a battery is applied in such a direction and of such a magnitude as to reduce the current in the short-circuited resistance instantly to zero, which becomes equivalent to closing the switch. This is performed electrically by connecting a battery as shown by the dotted lines; the armature and field currents produced give the change in their respective circuits.

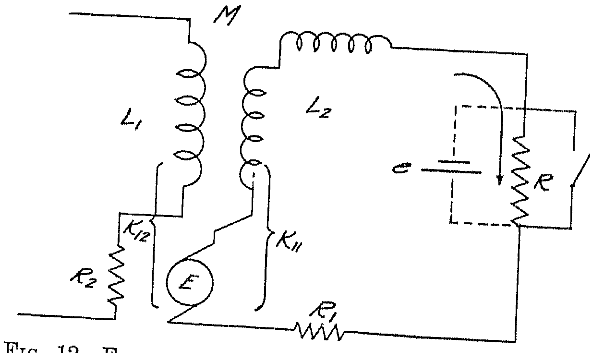
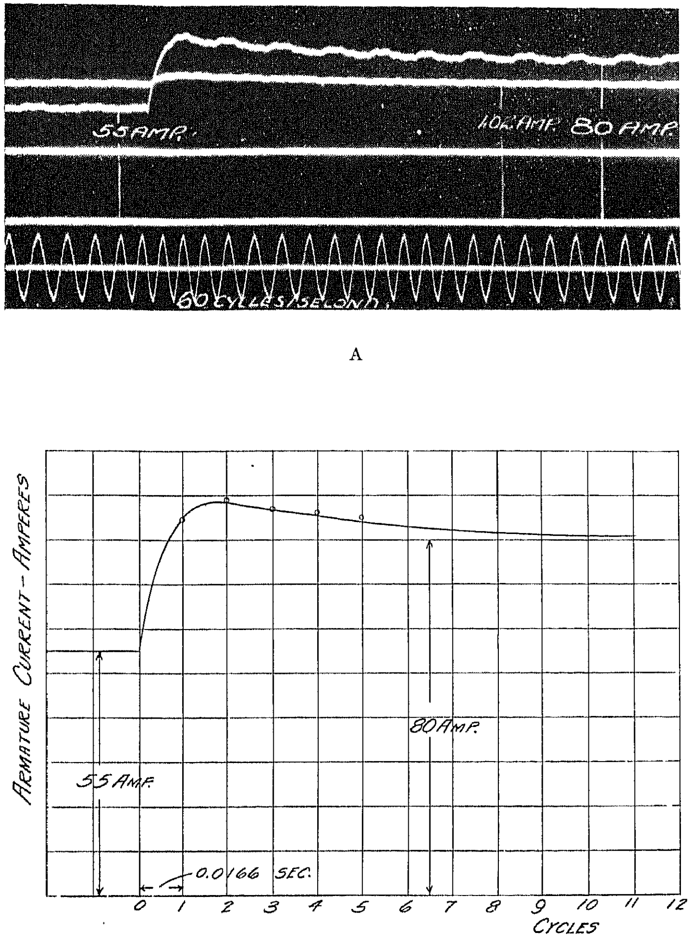


FIG. 12—EQUIVALENT CIRCUIT FOR SUDDEN CHANGE OF ARMATURE CIRCUIT RESISTANCE

This voltage would be

$$e = I_1R$$

where $I_1$ is the current initially in the short-circuited resistance $R$.



A

B

FIG. 13—ARMATURE AND FIELD CURRENTS WHEN ARMATURE CIRCUIT RESISTANCE IS CHANGED

A. Oscillogram of armature and field currents
B. Calculated graph of armature current
° Values from oscillogram

The equations for the change of current in armature and field circuit become

$$i_1 = \frac{(I_1R)\,(R_2 + L_2p)}{(R_1 + K_{11} + L_1p)\,(R_2 + L_2p) - (K_{12} + Mp)\,(Mp)} \quad \textbf{(13)}$$

$$i_2 = \frac{(I_1R)Mp}{(R_1 + K_{11} + L_1p)\,(R_2 + L_2p) - (K_{12} + Mp)\,(Mp)} \quad \textbf{(14)}$$

These currents, added to those previously existing, give the current actually in the circuit after the resistance is removed.

In a similar fashion the currents can be obtained in case a resistance is suddenly inserted in the circuit.

The solutions as indicated above are exactly the same as obtained when the machine is short-circuited; the currents are given by equations (3) and (4) in Appendix A, when the proper armature resistance is used. The graph of armature current in Fig. 13 is obtained in this fashion.

It is the contention that those machines having the smaller transient armature currents produce the better welding. The momentary change in the equivalent resistance of the circuit produces the transients as described above, and if the momentary change lasts sufficient time, would go through the same cycle. Consequently, if circuit conditions remain otherwise the same, a generator having the smaller overshoot in current on short-circuit would be the more desirable, and the study of these short-circuit currents has a direct relationship to the operating characteristics of the machine.

## References

1. *Design of Constant Current Generators for Arc-Welding,* K. L. Hansen, A.I.E.E., Vol. 39, p. 1357.

2. *The Neutralized Welder—A Means of Controlling Transients,* F. Creedy, A.I.E.E., Vol. 50, p. 662.

# Performance and Design of Electric Welders With Controlled Transients

BY F. CREEDY*
Member, A.I.E.E.

IT HAS been evident to engineers for some years past that the transient currents and voltages which occur due to the rapid changes taking place in the welding circuit should be minimized in order to get the best possible operation. Several types of apparatus have been built and tried out in practise in which these transients have been reduced and the verdict of the practical welder, both in this country and Europe, has been that such apparatus is more steady in operation than the older type of apparatus in which transients were not minimized. This is how the matter stands at the present moment. The belief in the advantages of minimizing the transients rests essentially on the verdict of the practical welder. Our first task, therefore, must be to translate this verdict into the language of the electrical engineer so that a perfectly definite problem expressed in his own language is placed before the designer of welding generators. One type of the new apparatus differs from the old only by means of a transformer interlinking field and armature circuit and so connected as to minimize or abolish the mutual induction between the two. It is easy, therefore, to test such a machine with and without the transformer, equivalent impedances being substituted where the transformer is not used.

Oscillograms of welding current show that the voltage frequently drops to zero when the arc is short-circuited by a drop of molten metal, there being usually a corresponding rise of current at this moment. One of the most important tests, therefore, would seem to be an oscillogram of a momentary short circuit on the generator. This can easily be arranged by connecting a switch across the terminals in series with a circuit breaker. As soon as the switch is closed the circuit breaker begins to carry a heavy current and accordingly opens. The result of such a test is shown in Figs. 1A and 1B in which *A* is the welding current, *D* the field current and *C* the volts across the short circuit. It will be seen that at the instant of short-circuit the volts drop to zero and remain there for about 5 cycles after which the circuit breaker trips and the voltage is restored.

Fig. 1B shows the machine without correcting transformer and Fig. 1A with transformer. It will be seen that the peak of current which occurs in 1B has been wiped out by the action of the transformer. This, in the writer's opinion, is the most useful effect produced by these devices for minimizing transients and in these oscillograms it is expressed in the language of the electrical engineer so that we are entitled to say that steady welding means absence of variation in the welding current. Much stress is frequently laid on the elimination of the overshoot, a peak of current which is found when the welding circuit is closed from open circuit (as for instance in Fig. 10C) where the current rises to 162 amps before falling to the steady value of 72 amps. It seems to the writer that the elimination of this overshoot is symptomatic instead of directly important. That is, a machine in which this overshoot is eliminated will have a small overshoot on momentary short circuit and where the overshoot is large on closing the circuit it will be large on momentary short circuit. Another point on which stress is often laid is rapid recovery after short-circuit. The immediate recovery in the first instant is of course provided by the discharge of the reactance (as shown for instance in Fig. 11A). But when the reactance has fully discharged, the voltage may fall to an unduly low value from which it only slowly recovers. This reduction is due to the fall of the field current shown at *D* and it is this fall after the reactance has discharged that we desire to eliminate. This is done in Fig. 10A, where it will be seen that the field current drops very much less than in Fig. 11A taken under exactly the same conditions and consequently the voltage *C* does not drop off so much.

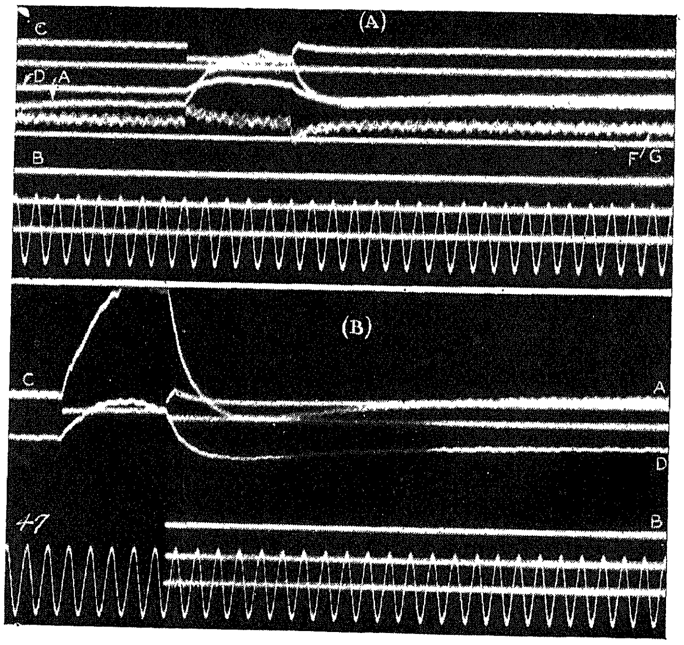


FIG. 1—MOMENTARY SHORT CIRCUIT WITH AND WITHOUT REACTOR TRANSFORMER

These are some of the benefits to be obtained by eliminating transients which, especially the former, are extremely important in practise.

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*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

The following investigations were made by means of two machines. (1) A "neutralized welder" of the type discussed in the writer's former paper* and a welder of standard design to which it was possible to apply a transformer in order to reduce the mutual induction between armature and field. This is referred to below as "the second machine." A photograph of the first machine is shown in Fig. 2 (which, incidentally shows the first American-built binary converter), its voltampere characteristics on steady current being shown in Fig. 3. The circuit diagrams for both machines are shown in Figs. 4 and 5.

## Discussion of Oscillograms

The main object of the designs now being discussed is to eliminate the surges of current which occur in the ordinary type of motor-generator set when circuit conditions change and particularly when a momentary short circuit is brought about, either by the electrode touching the work or by a drop bridging the arc.

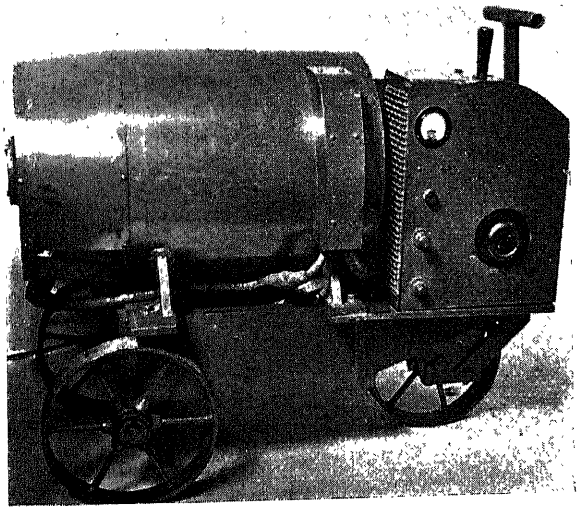


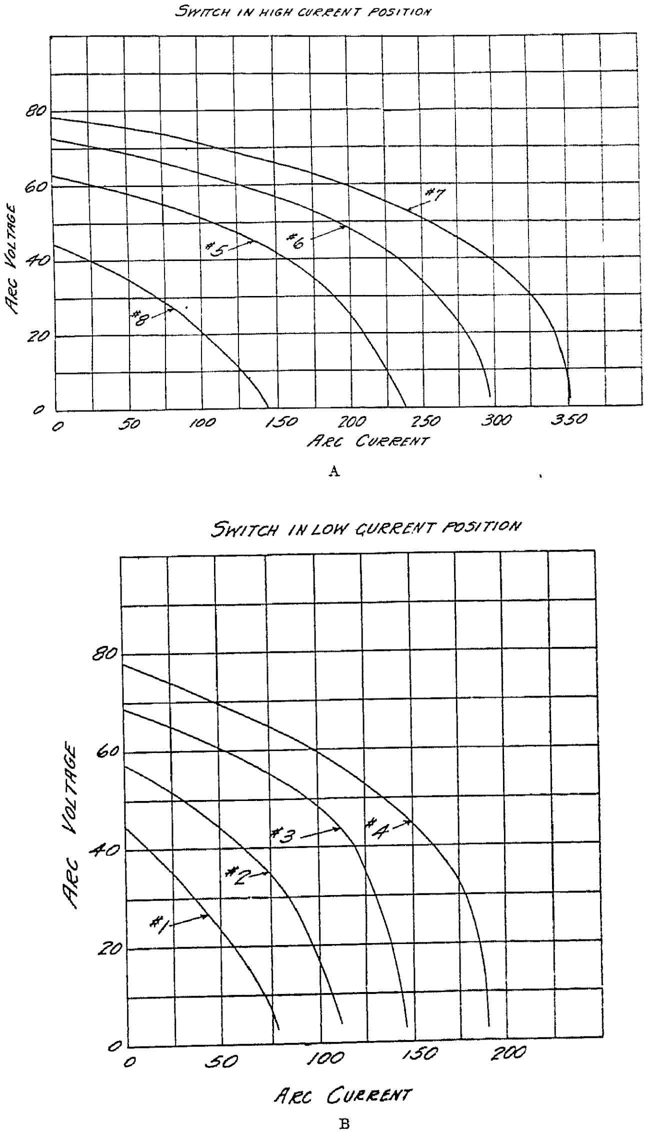
Fig. 2—The Neutralized Welder

In Fig. 6A is shown the effect of the momentary short circuit in the neutralized machine, *A* being the current, zero line *B*, *C* being the voltage and *D* the field current.

Fig 6B is a similar curve for a standard type of welder (referred to as "the second machine"). At the bottom is shown a 60-cycle timing wave so that the distance between nieghboring maxima is 1/60 of a second. These are perhaps the most striking oscillograms of the series. They show that in the neutralized machine the maximum increase of current, when an arc across which there is a drop of about 20 volts is short-circuited, is about 33 per cent whereas the corresponding rise in the second is 100 per cent. This means that in the neutralized machine the power flow is increased in the ratio of 1 to 1.76 while in the other it is increased in the ratio of 1 to 4.

The next series show the effect of a permanent short circuit suddenly applied to the machine when carrying 150 amperes and about 20 volts. Two things are noticeable in Fig. 7A which represents the neutralized machine; *A* being the current as before with zero line *B*, *C* the volts, and *D* the field current. The short circuit is applied at the left and it will be seen that the current rises about 33 per cent and then gradually settles down again to its original value. This is because the machine is so designed as to have a constant current characteristic for slow variations as is shown by its voltampere characteristic curves, (Fig. 3). Consequently after it has been given time to adjust itself, the current after short circuit is the same as before.

Fig. 7B represents the second machine and again two things are noticeable. Starting with 150 amperes and 20 volts as before, when the short circuit is applied the current rises to about double its original value (power



Figs. 3A and 3B—Voltampere Characteristics of Neutralized Welder

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*The Neutralized Welder*, by F. Creedy, A.I.E.E. Trans., June 1931, p. 662.

multiplied 4 times) and then after about 16 or 17 cycles of the timing wave falls to a value of 1.55 times the original. Thus in such a machine the effect of a permanent short circuit is a double one. (a) It causes a surge of about 100 per cent in excess of normal and (b) it causes a permanent rise of current of about 55 per cent in excess of normal unlike the neutralized machine where the final current is the same as the initial current.

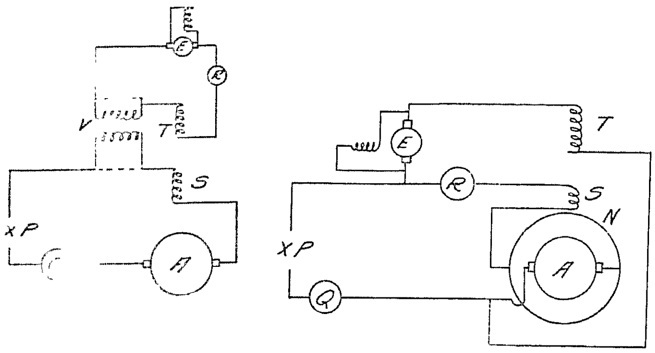


Fig. 4—(Left) Separately Excited Welder
Fig. 5—(Right) Neutralized Welder

A armature
N neutralizing winding
S series coil
T shunt and/or separate excitation
E exciter
R regulating rheostat
Q reactance
P arc
V transformer (dotted lines show how it may be cut out)

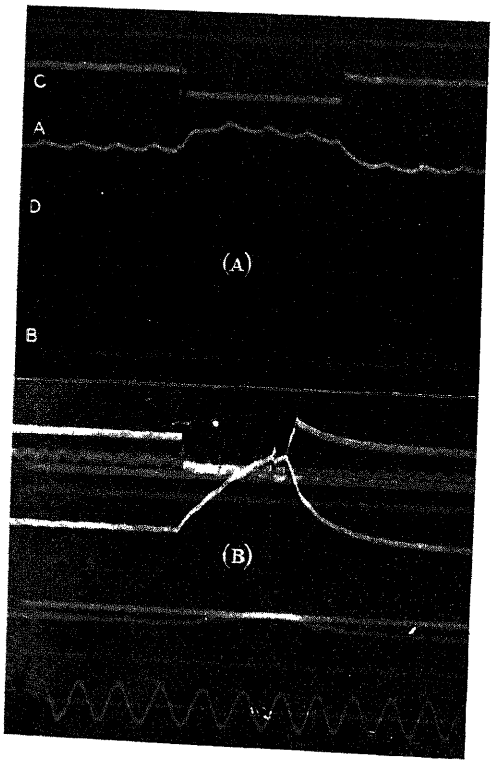


Fig. 6—Momentary Short Circuits on Two Different Machines

Machines with constant-current characteristics are by no means new, of course, but the present design eliminates the disadvantages of older constant-current machines by enormously reducing the self-induction of the shunt-connected coil, thus enabling it to follow rapid variations in a way the older types could not.

The next curves show the effect of suddenly opening the circuit.

Fig. 8A shows the effect of suddenly opening the circuit on the neutralized machine. *A* being the current, zero line *B*, *C* the voltage, and *D* the field current; *E* being the voltage directly across the brushes. It will be seen that when the current stops, the first effect is a rapid rise of voltage due to the discharge of the reactance, the voltage momentarily rising to a value considerably higher than normal. The voltage then falls to normal and continues at a constant value apart from small oscillations due to the generator teeth, etc. Meanwhile the field current has risen to the new value corresponding to the higher voltage of the circuit and this takes approximately 2½ cycles of the timing wave or 0.04 seconds.

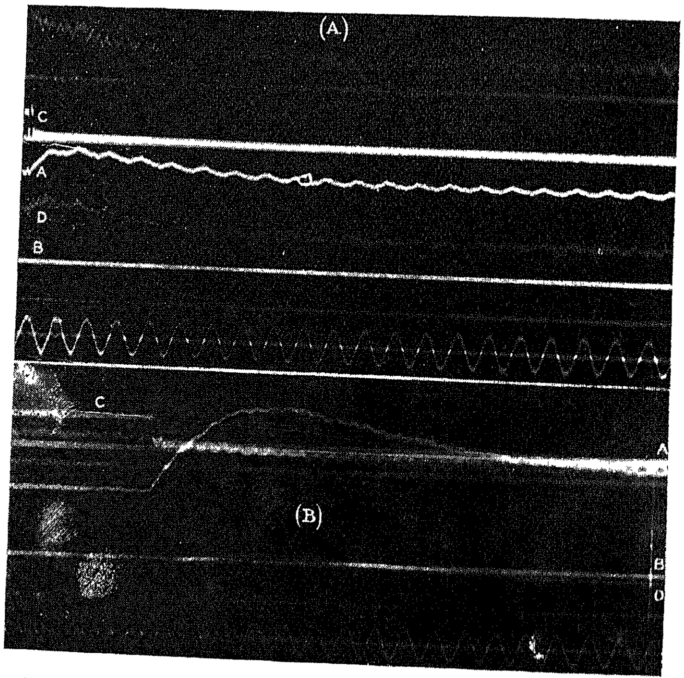


Fig. 7—Permanent Short Circuits on Two Different Machines

Fig. 8B is a similar curve in which the same phenomena are shown to a larger scale. The most important thing to notice is that by the time the current has reached zero, the voltage has risen up to or beyond the open-circuit value. This is true of any machine which has a large reactance as will be seen in a moment. But the special feature of this machine is that by the time the reactance has finished discharging the machine has picked up its voltage so that it is able to maintain it constant after this. In this oscillogram as stated *C* is the voltage across the terminals while *E* is the voltage across the commutator of the machine that is without taking the reactance into account. This voltage is nearly proportional to the field current and the rapid rate of growth should be noted.

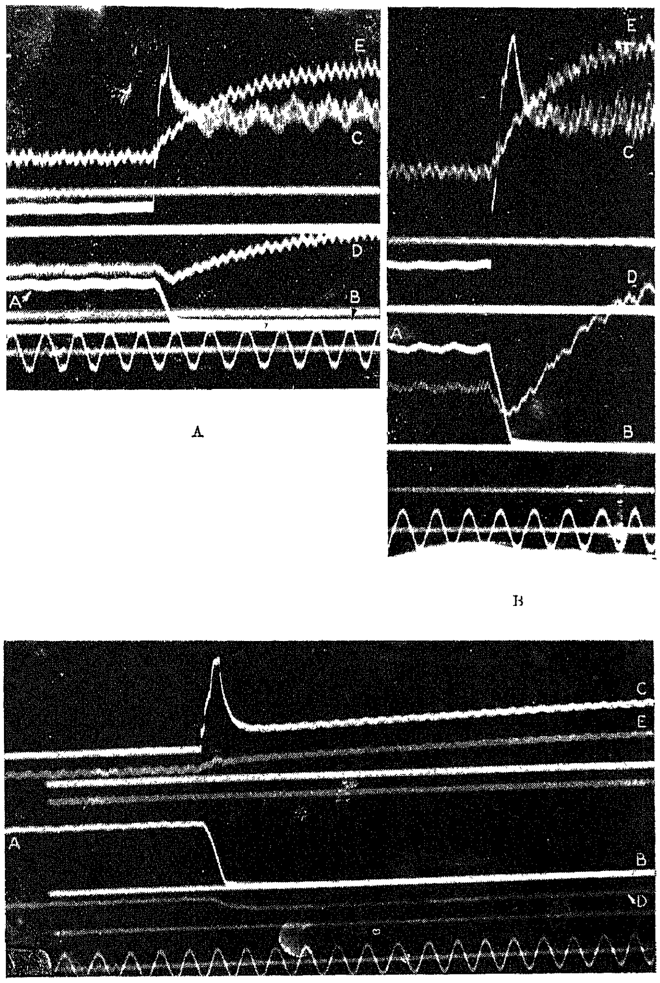
Fig. 8C gives the corresponding series of curves for the second machine, *A*, *B*, *C*, *D*, and *E* having the same meaning as before. Here we see the same kick of voltage when the current suddenly stops and the reactance discharges, but when the reactance has discharged the machine has scarcely begun to pick up its voltage and it will be seen that the voltage curve *C* is slowly rising as we proceed towards the right and after 14 cycles or 0.23 seconds it is found not yet to have reached the steady state.

The practical meaning from a welder's point of view of this group of oscillograms is to show the rates of recovery of the two machines required so that if the arc is momentarily extinguished by short circuit, the moment the short circuit is removed the arc shall reestablish itself and it will not be necessary to wait for the machine to build up before obtaining the arc again.

FIG. 9B shows the current in the neutralized machine starting from open circuit, the lettering having the same meanings as before. It will be seen that the current simply rises from zero to its steady value and remains there without any surge whatever. At the same time the voltage drops to slightly less than its steady value and then recovers within two cycles or 0.033 of a second.

Fig. 9A shows the same phenomena in the second machine. In this case current rises to a value about 50 per cent higher than normal and then falls slowly to normal in about 14 cycles or 0.23 seconds. Simultaneously the voltage falls to about 1/3 normal and in about 2½ cycles reaches a value about 50 per cent higher than normal, finally dropping to normal in about the same period of 14 cycles.

The next set of oscillograms show tests on the set referred to above as the "second machine" but fitted with a transformer reactor adapted to its constants. It should be clearly understood that this machine was not designed for use with a transformer reactor and therefore although the characteristics of such an apparatus can very well be demonstrated by its means, yet if the design could have been modified in the manner described in the writer's previous paper,* namely by reducing the reluctance of the magnetic circuit and making the other changes referred to in Appendix I of that paper, very much superior results could have been obtained. Some of the oscillograms reproduced below seem to give characteristics of a not very favorable type but these in all probability do not characterize commercial machines fitted with a transformer reactor since in these machines the generator and transformer are especially designed to suit one another.



A

B

C

FIG. 8—OPEN CIRCUIT ON TWO MACHINES

In the oscillograms, Fig. 10C shows the machine operated without the transformer reactor but with resistance equal to that of the transformer secondary inserted in the field in its place. It will be seen that when the current is switched on, there is a very marked rise in the first few instants, soon settling down to steady value. In this diagram the lettering is the same as that used previously. Fig. 10B shows the effect of closing the circuit when the transformer reactor is used. It will be seen that the increased value of the current which characterized Fig. 10C has now been entirely eliminated. The current now simply rises to a steady value and remains there. The lettering is the same as before save that the voltage across the secondary of the transformer has also been recorded in curve *F* zero line *G*. Under steady conditions the voltage across this secondary is simply the *IR* drop equal to about 150 volts. The most striking thing about this curve is the high peak of voltage at the moment of closing the circuit. This amounts to approximately 1,000 volts in this test. Fig. 10A shows the effect of suddenly opening the circuit with the transformer reactor in circuit. The lettering is the same as before and it is noticeable that we also get a high-voltage kick when the circuit is open, in this case amounting to about 1,160 volts. Referring to curves *C* and *D* which show the terminal voltage and the field current, we see that as soon as the circuit is open a considerable kick of voltage is formed by the discharge of the reactance exactly as in Fig. 10B. When the reactance is discharged, the field begins to increase in the fashion normal in any d-c machine and at the end of 23 cycles it has not yet attained a steady state. Thus these tests do not confirm the claim which is often made that the transformer reactor enables a machine to pick up more rapidly than it otherwise could. In fact this seems obvious from first principles. All a transformer can do is to supply a short period impulse which ends when the armature current becomes constant. If the field current has not reached a steady value by the time the armature current has ceased to vary, the transformer can not help it because it becomes inert as soon as the armature current becomes constant. The source of the improvement must be looked for in another direction. In Fig. 10A the field current (and hence field volts) does not drop off so much as it does in Fig. 11A (no transformer reactor) and hence the field starts to recover from a higher point. In other words since the mutual inductance is less in Fig. 10A there is less change in field current. During the above tests the armature current had the value of 75 amperes.

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*loc cit.

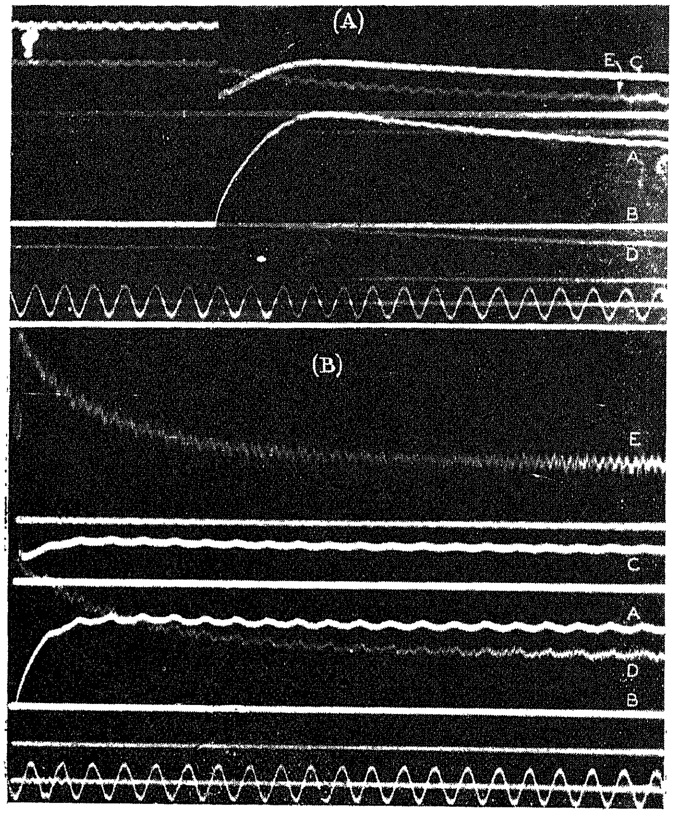

Fig. 9—Current Rise on Closing the Circuit on Two Different Machines

Since a large continuous current flows through the primary circuit of the reactor transformer during its operation, it would seem at first sight that the iron must be highly saturated and it was thought desirable to study the effect of introducing a variable air gap into the magnetic circuit of the transformer. Figs. 12, 10A and 11C show corresponding oscillograms for cases where the air gap had values of zero, 1/8 in. and 1 in. respectively. Comparing these we perceive that the differences are quite slight. These show the effect of breaking the circuit. Numbers 10B and 11B correspond to 1/8 in. and 1 in. air gaps respectively and show the effect of making the circuit. These again are quite similar and it would therefore seem that an air gap in the magnetic circuit does not exert any important influence. These also show the same high voltage, that in Fig. 11C being 800 volts while in Fig. 11B the voltage is 950.

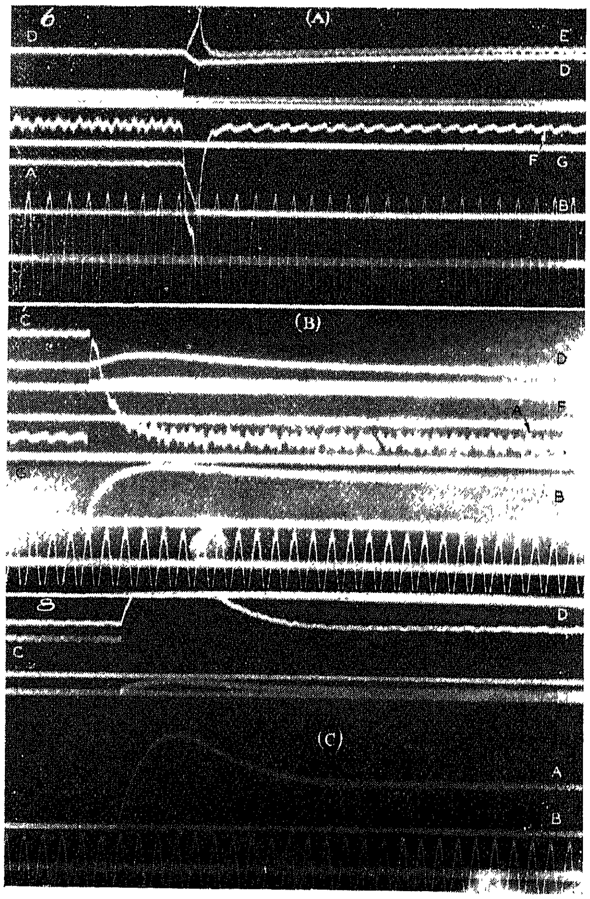

Fig. 10—Current Rise on Closing the Circuit When Transformer Reactor is Used

Having determined that the length of air gap does not exert an important influence, later tests were taken with the air gap of 1/8 in. Figs. 10B and 13A show the effect of closing the circuit with currents of 75, and 156 amperes. The voltages corresponding to these tests were 850 and 2,500 respectively.

Figs. 10A and 13B show the effect of breaking circuit under similar conditions. The voltages in these cases being 850 and 2,200. As expected these voltages are roughly proportional to the current and therefore at 300 amperes one would anticipate a voltage of approximately 4,000 to 5,000 volts.* It should be repeated here that voltages as high as this are unlikely to be found in commercial machines and it would be of interest to know just what the voltages are in practical cases. It is clear that since such a high-voltage kick can only be balanced by a corresponding kick in the field circuit, these voltages must also appear across the field which would make handling the machine during operation very dangerous to life unless something were done to modify them.

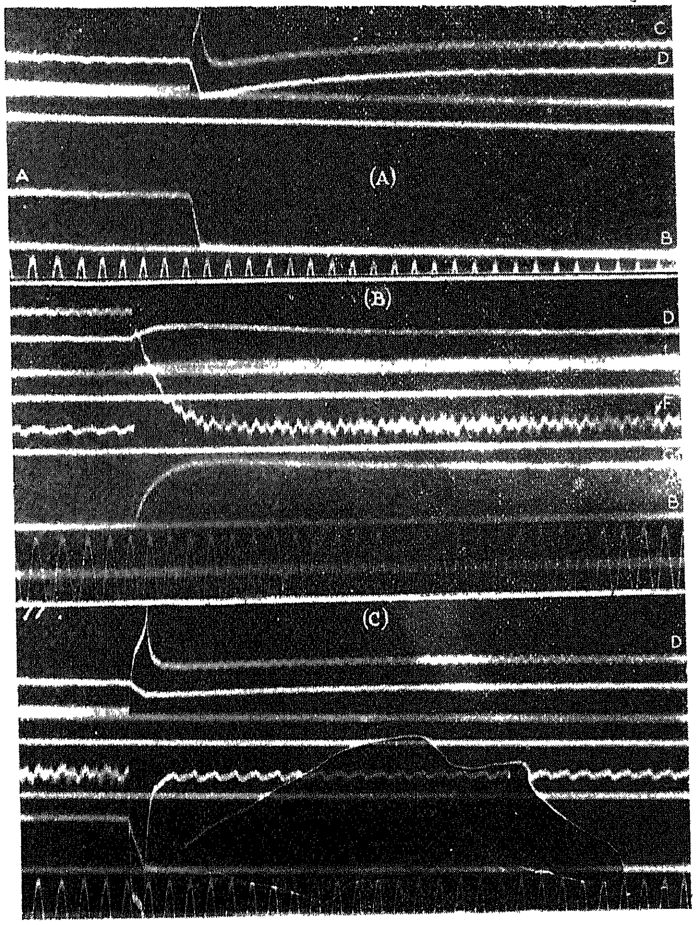

Fig. 11—Opening the Circuit With Transformer Reactor

Thus we find that somewhat similar results can be obtained, either by the use of the transformer (but at the expense of high-voltage kicks) or by the inherent design of the machine without any transformer or voltage kick. We have now to investigate how this comes about. Let us first study the closing of the circuit from an open-circuit condition. If we make a mathematical analysis such as is given in my paper mentioned previously, we find that the current immediately after the circuit is closed is made up of 3 components:

1. A steady state component.
2. The armature transient—a component containing a rapid logarithmic decrement whose rate of decrease is approximately such that the transformer volts induced by the decay of the flux interlinking the series winding and that interlinking any external reactances there may be, shall balance the rotation volts. This transient is always opposed in direction to the steady-state current. This may easily be shown by considering the case where the field current does not vary at all.

Equation (**51**)—Appendix I of the former paper is

$$\frac{n_1^2}{p}\,\frac{di_{33} - i_1}{dt} + Kn_1\,(i_{33} - i_1) - L_0\,\frac{di_1}{dt} = 0$$

If $i_{33}$ is constant (no mutual induction)

$$Kn_1 i_{33} = K_{n1} i_1 + \left( L_0 + \frac{n_1^2}{p} \right) \frac{di_1}{dt}$$

The solution of this is if $K_{n1}L_{33} = E_1$ the rotation volts due to the field current

$$i_1 = \frac{E_1}{K_{n1}} \left( 1 - e \frac{-K_{n1}t_2}{L_0 + \frac{n_1}{p}} \right)$$

Thus the armature transient is necessarily opposed to the steady-state current.

3. The field transient due to the variation of the current in the field. This will always be in the same direction as the steady-state current. Its rate of decrement is such that the sum of the transformer volts due to the variation of the main flux interlinking the field winding and any fluxes interlinking external reactances will balance the resistance volts (or resistance and rotational volts in the shunt type of machine). In proving that this field transient must always be in the same direction as the steady-state current, it should be pointed out that there is a slight error in Fig. 3 of my former paper, reproduced, corrected in Fig. 14. This may be taken as before to refer to a separately excited machine in which flux changes are due entirely to changes in the current in the series coil. If the series current suddenly changes from $I_a$ to $I_b$ then for the case of little or no

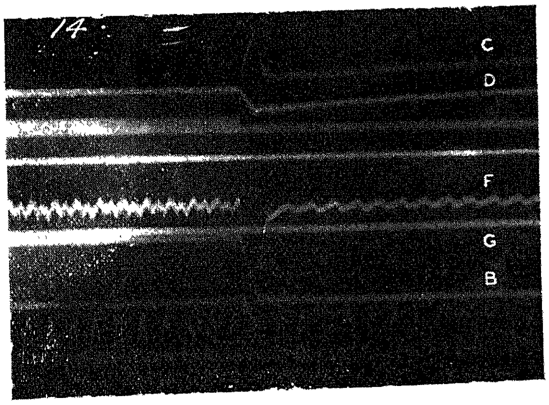

Fig. 12—Open Circuit with Zero Airgap in Transformer

leakage the change in ampere turns is instantly masked by transient currents in the separately excited coil (shown at *F*) so that at the first instant there is no resultant change in flux. Since the series and separately excited coils are wound in opposition, this involves a momentary increase in the field current which is confirmed by the oscillograms of Fig. 10C for instance, or many others.

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*In all these tests the circuit was opened by opening a circuit breaker and closed by closing the same breaker by hand. The speed of opening or closing can be determined from the oscillogram.

Thus these three components are shown in Fig. 15, *A* being the armature transient, *S* the steady component and *F* the field transient, and their sum must be zero at the moment of closing the circuit. Adding them up as shown *dotted* we clearly get a curve which may have any degree of overshoot just as we find in practise. It will be clear that we can control the rates of decrement of these transients in several ways. By increasing the external inductance in the armature circuit we can slow down the armature transient as at *B* and by increasing the resistance or reducing the inductance in the field circuit we can increase the rapidity of the field transient as at *G*. Clearly if the armature transient is made slower the overshoot will be less and the same follows if the field transient is made more rapid. Figs. 13C and 13A only differ because in the former the external reactance is cut out. Yet the overshoots are 220 per cent and 140 per cent respectively.

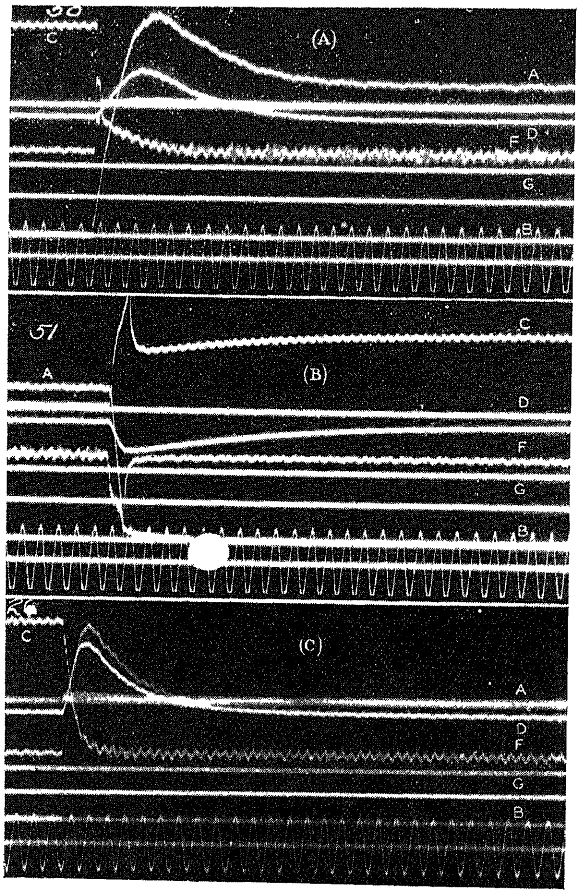

FIG. 13—FURTHER TESTS WITH REACTOR TRANSFORMER

Clearly it is the field transient that is responsible for the overshoot since if it were zero, overshoot would be impossible, and if we can reduce or eliminate this, we shall get rid of the overshoot. The field transient, however, only exists and appears in the armature circuit in virtue of the mutual induction between the two as was shown in the short investigation just given. Consequently if we reduce the mutual induction to zero or as low as possible, we can eliminate the field transient from the armature circuit and this can be done no matter how great its magnitude.

Another plan, however, will be to design the machine so that the field transients are inherently of small magnitude and these two plans correspond to the two machines tested. These are discussed in turn.

The constants of the two machines under certain conditions are as follows:

| | Neutralized welder | Second machine |
|---|---|---|
| Rotation volts per ampere in series winding and resistance of series circuit | 0.348 | 0.70 |
| Rotation volts per ampere in shunt winding | 14.5 | 55.0 |
| Coefficient of self-induction of armature circuit (with reactor) | 003.0 | 009.0 |
| Coefficient of self-induction of field circuit | 1.26 | 27.9 |
| Resistance of field circuit | 6.4 | 260.0 |
| Coefficient of mutual induction between shunt and series | 0.03 | 0.3 |
| | 0.0045 without reactor | |

In order to form a clearer physical idea of the balance of voltages under transient conditions in these machines, we may take advantage of the fact several times pointed out theoretically and confirmed experimentally by Professor A. R. Miller that these transients may sometimes take an oscillatory form. It has long been known (see for instance Steinmetz, A-C phenomena, Appendix II) that alternating current methods of analysis (including the vector diagram and the "symbolic" method) can be applied to these currents and we shall accordingly endeavour to draw the vector diagram for this case. In the ordinary vector diagram the instantaneous values of the function are obtained by causing the vector diagram as a whole to rotate at uniform speed, the extremity of each vector tracing out a circle, and projecting each vector on a fixed axis. In the oscillatory vector diagram the extremity of each vector must trace out a logarithmic spiral and thus the diagram must be conceived as shrinking as it rotates all its component vectors however, preserving the same relative magnitudes and phases. In drawing the diagram itself the chief difference is that an inductive voltage $L\frac{di}{dt}$ no longer lags 90 deg behind its current but *more* than 90 deg thus representing the fact that the decrease of the flux continually yields up energy. In fact if

$$i = Ie^{jqt} \quad L\frac{di}{dt} = jLqIe^{jqt}$$

$$\text{but if } i = Ie^{(-a+jq)t} \quad L\frac{di}{dt} = (-a + jq)\, LIe^{(-a+jq)t}.$$

In developing this vector diagram it will be convenient to state the constants in a form corresponding to an equal number of turns on the series and separately excited fields. Clearly $K_{11}/K_{12}$ is the ratio of turns on these coils. Multiplying $K_{12}$ and $M$ by this ratio and $L_2$ by its square we get

| for the "second machine" | for the neutralized welder |
|---|---|
| $K_{11} = K_{12} = 0.66$ | $K_{11} = K_{12} = 0.348$ |
| $L_1 = 009$ | 003 (in example 0.00096) |
| $M = 0041$ | 0007 |
| $L_2 = 0052$ | 0007 |
| $r_2 = 05$ | 0036 (in example 0.025) |

Making use of these constants the equations read

$$(r_1 + K_{11} + L_1p)\, i_1 + (K_{11} + Mp)\, i_2 = 0 \qquad (1)$$

$$(\qquad Mp\, i_1 + (r_2 + L_2p)\, i_2 = 0 \qquad (2)$$

In these equations $p$ is to be understood not as $\frac{d}{dt}$ but as a complex quantity whose value may be ascertained as follows.

Let

$$i_1 = 100\, e^{(-20.3+33.25j)t} \text{ an oscillatory function}$$

$$\frac{di_1}{dt} = (-20.3 + 33.25\, j)\, i_1$$

$$\text{Therefore} \qquad p = -20.3 + 33.5\, j.$$

Further a plus sign has been placed before the terms containing $i_2$ since in drawing the vector diagram we wish to follow alternating-current conventions. It is usual in a 1:1 transformer to denote the resultant of primary and secondary currents by $i_1 + i_2$ notwithstanding that the currents are opposite in direction whereas in d-c practise the resultant of two opposing currents is denoted by $i_1 - i_2$. We may now readily calculate the various quantities concerned.

$$Ki_1 = 66$$

$$Mpi_1 = -8.4 + 12.6\, j$$

$$L_1pi_1 = -16.8 + 25.2\, j$$

$$r_2 = i_2p = -055 + 0.172\, j$$

$$L_2 = -88 - 25\, j$$

$$Ki_2 = -58.2 - 16.6\, j$$

$$L_1 + i_2 = 12 - 25\, j$$

$$K(i_1 + i_2) = 7.8 - 16.6\, j$$

These are shown in the accompanying diagram in which $i_1$ (half scale) is shown at $OI_1$ on the right. $L_2pi_1 = OE_{11}$ the emf of self-induction now lags *more* than 90 deg since we have an oscillating circuit. $OE_{12} = Mpi_1$ is in the same direction but of reduced length. The current $OI_2 = i_2$ must be such that its resistance $E_{21}E_{22}$ and reactance volts $OE_{21}$ sum up to a quantity equal and opposite to $Mpi_1$, *viz.*, to $OE_{22}$. Thus the second equation is satisfied. The first equation states that

$$-\{ K\,(i_1 + i_2) + Mp\,(i_1 + i_2) \} = i_1\,(r_1 + L_0p).$$

Adding $OI_1$ and $OI_2$ we get $OI_0 = i_1 + i_2$. $K\,(i_1 + i_2)$ is shown at $OE_{13}$ and $Mp\,(i_1 + i_2)$ at $OE_{14}$. It will be seen that their sum is equal and opposite to $OE_{15} = L_0pi_1 = (L_2 - M)\, p_{21}$.

In studying this diagram it will be convenient to conceive that armature and field current each produces its own flux just as if the other were absent, these two fluxes then combining to form the resultant observable flux. In the field circuit then the voltage $Mpi$ induced by the armature current is balanced by the field impedance drop $(r_2 + L_2p)\, i_2$ in the usual manner. In the armature circuit two points of view are possible.

1. As shown more clearly in the diagram, the rotation voltage due to the resultant current $(i_1 + i_2)$ plus the inductive voltage induced in the armature by the main flux are balanced by the armature resistance drop and inductive voltage due to the leakage reactance. It is clear from this that balance can not be obtained without a considerable leakage self-induction in the armature and this explains why this is required to obtain an oscillatory solution.

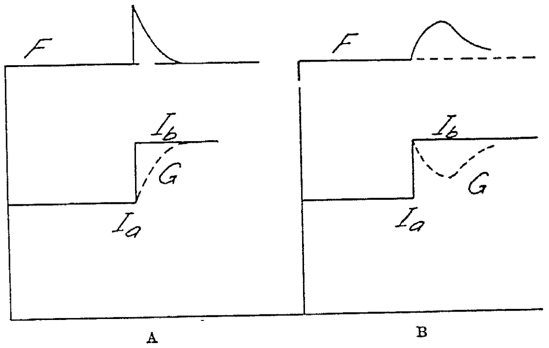

FIG. 14—EFFECT ON FIELD OF SUDDEN CHANGE IN ARMATURE CURRENT

2. A second point of view of course would be that all quantities proportional to armature current are balanced by all quantities proportional to field current.

In the above equations it will be noted that we have equated the transient voltages round both field and armature circuits to zero. All the external emfs are balanced by the potential drops and rotation voltages due to the steady currents and hence it follows that the sum of the transient voltages round the circuit is zero. Here of course $i_1$ and $i_2$ must be held to exclude any steady-state components. If they did not we could not of course apply the vector diagram to them.

This diagram may be regarded as a complete substitute for the treatment of the subject by differential equations which is of course extremely general but extremely cumbrous. Eliminating $i_2$ from equations (**1**) and (**2**) we get

$$(r_1 + K_{11} + L_1p)\,i_1 - \frac{(K_{11} + Mp)\,Mp}{r_2 + L_2p}\,i_1 = 0$$

Omitting $i_1$, rearranging the quantities according to powers of $p$ and solving the quadratic so formed we get

$$p = \frac{K_{11}M - (r_1L_2 + L_1r_2)}{2\,(L_1L_2 - M^2)}$$

$$\left(1 \pm \sqrt{1 - \frac{4\,(L_1L_2 - M^2)\,(K_{11} + r_1)\,r_2}{r_1L_2 + l_1r_2 - K_{11}M}}\right)$$

This is of course identical with that derived from the differential equation and so far we have nothing new. In any numerical case it perhaps provides the simplest way of calculating $p$.

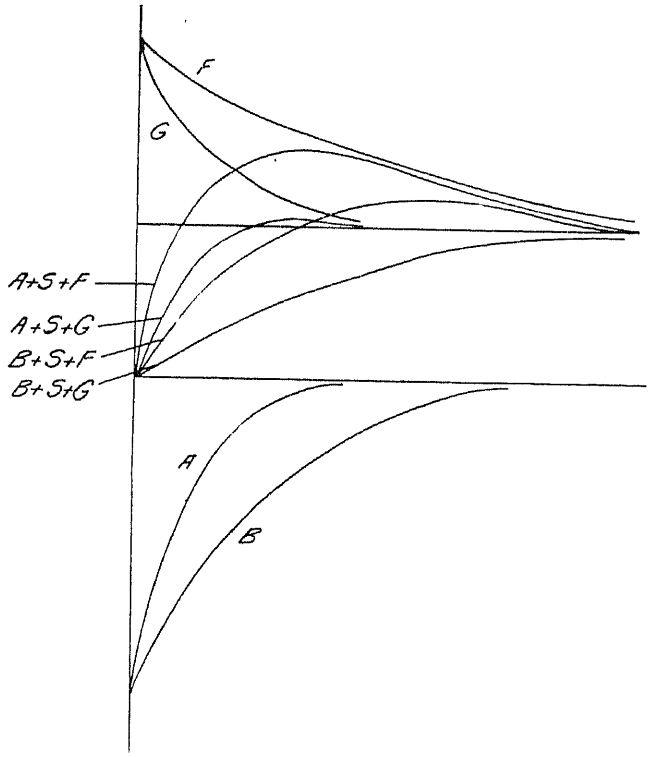

FIG. 15—HOW THE CURRENT SURGE IS MADE UP

A more geometrical method of determining $p$ is the following: In any quadratic whose solution is imaginary the usual formula

$$x = -b \pm \sqrt{b^2 - c}$$

may be written

$$x = -b \pm j\sqrt{c - b^2} = Re^{j\theta}$$

In this case

$$R^2 = b^2 + (c - b^2) = c$$

summing the squares of real and imaginary parts.

Regarded geometrically this appears as follows: In the triangle $ABC$

$$AB = \sqrt{c}$$
$$AC = -b$$
$$BC = \sqrt{c - b^2}$$
$$\tan\theta = \sqrt{c - b^2}/b.$$

Consequently $AB$ represents $p$ and knowing $c$ and $b$ it may be determined by this construction without calculation from the formula. In our case

$$c = \frac{(K_{11} + r_1)\,r_2}{L_1L_2 - M^2} \text{ and } -b = \frac{K_{11}M - (r_1L_2 + r_2L_1)}{2\,(L_1L_2 - M^2)}$$

But in place of determining the arbitrary constants either by simultaneous equations or by the Heaviside expansion theorem we have a much simpler process. Suppose the terminal conditions are:

When $t = 0$ . $i_1 = a$ units (say — 75 amps for instance)
$i_2 = b$ units (say zero for instance)

To satisfy these conditions we have merely to choose our axis of projection (in the case where $i_2$ is zero when $t = 0$) so as to be perpendicular to $i_2$ on the diagram as at $AB$ and our scale so that the projection of $OI_1$ on $AB$ is 75 units. Clearly we can find an axis of projection such that the projections of $OI_1$ and $OI_1$ on it bear any ratio whatever to suit any desired terminal conditions, and a scale to suit any case we desire to

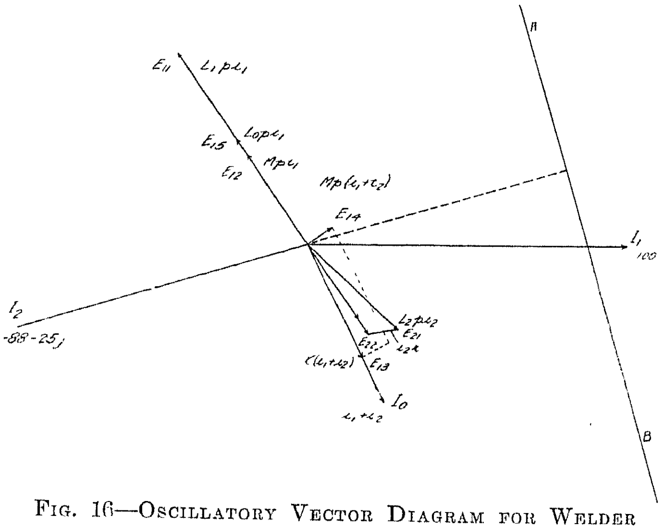

FIG. 16—OSCILLATORY VECTOR DIAGRAM FOR WELDER TRANSIENTS

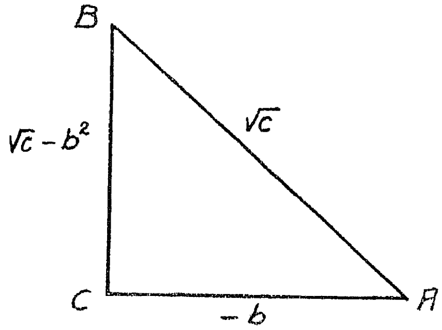

FIG. 17—GRAPHIC SOLUTION OF QUADRATIC IN "p"

study. The vector method therefore is a complete substitute for the method of differential equations in the study of oscillatory transients not only in this but in all other cases (not involving equations of higher than the second order) in which they occur.*

In endeavouring to discuss the case of "real roots" we must return to direct-current conventions if our results are to have the accustomed form. Thus the equations will be

$$(r_1 + K_{11} + L_1 p)\, i_1 - (K_{11} + Mp)\, i_2 = 0$$

$$Mpi_1 - (r_2 + L_2 p)\, i_2 = 0$$

Now it is clear that when the vector representing an inductive voltage lags 180 deg behind its current the oscillatory solution becomes exponential and the above diagram encourages us to try and form an equivalent for the exponential case.

Let

$$i_1 = 639\epsilon^{-50.4t} - 715\epsilon^{-103t}$$

$$i_2 = 630\epsilon^{-50.4t} - 630\epsilon^{-103t}$$

When $t = 0$

$L_1 = -76$ $\quad Mpi_1 = 168$

$L_2 = 0$ $\quad L_2pi_2 = +168$

$K_{11}L_1 = -50$ $\quad Mpi_2 = +133$

$L_1pi_1 = 185$

Since $i_2 = 0$, $i_2r$ and $K_{11}i_2$ are both zero which simplifies the equations. This leaves only three terms in the armature equation

$$K_{11}L_1 + L_1pL_1 - Mpi_2$$

$$-50 + 185 - 133 = 0$$

The diagram which of course is a straight line shows that $Mpi_2$ is in the same direction as $K_{11}i_1$. Since it has to be balanced by $L_1pi_1$ unless $L_1$ is very great this will demand very rapid change in $i_1$. If we reduce either $M$ the mutual induction or $pi_2$ the rate of change of $i_2$ then $L_1pi_1$ need not be so great and $i_1$ may vary more slowly.

Now take a case where the slope of the field current is negative

Let

$$i_1 = -79\epsilon^{-154t} + 28\epsilon^{-50.4t}$$

$$i_2 = 100\epsilon^{-154t} - 100\epsilon^{-50.4t} -$$

$$pi_2 = -15{,}400\epsilon^{-154t} + 5{,}040\epsilon^{-50.4t}$$

When $t = 0$

$i_1 = -51$ $\quad L_1pi_1 = 10.35$

$i_2 = 0$ $\quad Mpi_1 = 7.5$

$K_{11}L_1 = -17.6$ $\quad L_2pi_2 = -7.22$

$Mpi_2 = -7.22$

For the same reasons as in the last paragraph the equation for the armature circuit reduces to

$$K_{11}L_1 + L_1pL_1 - MpL_2 = 0$$

$$-17.6 + 10.35 + 7.22 = 0$$

Thus in this case $Mpi_2$ the voltage due to the decrement of the flux due to the field alone aids that due to the decrement of the armature flux to balance the rotation volts. If therefore a fairly large external reactance is employed the rate of decrement of the fluxes may be made relatively small and if the machine is designed with low values of $L_1$ and $M$ all the transient voltages in the machine itself may be kept very small, the external reactance setting the pace of current changes and the machine following as rapidly as if it contained nothing but resistance. Incidentally a machine so designed requires far less material than the more traditional type. If the field current fell off with sufficient rapidity its voltage $Mpi_2$ might be sufficient by itself to balance the rotation volts. In this case the armature transient current would disappear altogether, the armature current instantaneously assuming its steady value. The nearer we approach this case *i. e.*, the more rapid the decrease of the field current, the smaller will be the armature transients, and the more rapid the rise of the current (without overshoot) to its final value.

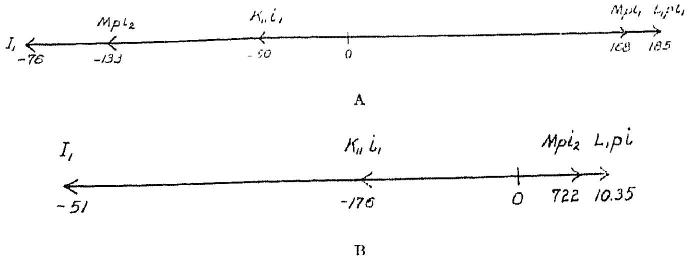

FIG. 18—NON-OSCILLATORY DIAGRAMS FOR WELDER TRANSIENTS

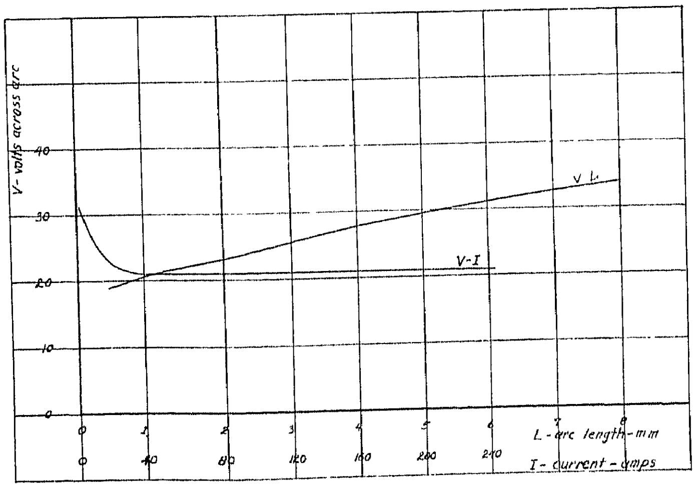

FIG. 19—ARC VOLTAGE PLOTTED AGAINST CURRENT

Thus we see that if the field current *rises* when the armature circuit is closed the inductive voltage from the field circuit aids the rotation volts in the armature and a very rapid rate of variation of armature current (with consequent overshoot) is necessary to balance them. Overshoot is essentially due to the field current rising. If we make arrangements for the field current to *fall* as in the neutralized machine tested the field inductive voltage will help to balance the rotation volts, and no very great rate of variation of armature current is necessary with consequently no overshoot. This is amply confirmed by the oscillograms.

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*For the actual plotting of the transient it is probably most convenient to derive the solution from the diagram and plot it as if there were no decrement. Then multiply the ordinates by $\epsilon^{-at}$ remembering that this is unity when $t = 0$.

But the machine, to be practical, must have quick recovery as well as absence of overshoot. The cause of slow recovery as we have seen was the drop in field current after the armature circuit is opened and the slow "pick-up" of the machine of traditional design when once the field current has fallen off. For this reason we endeavour in the old type of machine to prevent the field current from falling by means of the transformer. On the other hand in the neutralized type we provide a machine with constants such as shall enable the field current to rise at the rate demanded by practical requirements as soon as the armature circuit is opened. Thus having a machine inherently capable of quick recovery we need not be afraid of the field current falling off and can use reduction of the field current as a means of preventing overshoot.

Finally to sum up there are essentially two methods of eliminating transients.

### TRADITIONAL DESIGN WITH CORRECTING TRANSFORMER

According to this plan, the design of the field circuit is not of very great importance since whatever happens it can always be set right by an adequate transformer. It is possible therefore to continue to design it on traditional lines with the usual large number of turns, small current and high reluctance magnetic circuit involving high field ampereturns. The result of doing this, however, is to necessitate the use of a transformer which must produce several thousand volts in order to counteract the field voltages resulting from high field self-induction, a result, which as already stated, seems to the writer not only expensive but dangerous to life.

### A MACHINE INHERENTLY DESIGNED TO HAVE SMALL TRANSIENTS

According to this plan every care is taken in the design of the machine to make all its inductances as low as possible, especially that of the field. In order to do this, special pains are taken to minimize the reluctance of the magnetic circuit thereby permitting a small number of turns on the field.

Since although these inductances are small thay can create fairly high voltages if the current varies very rapidly, it is desirable even in such a machine to slow down the armature transient by means of heavy external self-induction. Thus we have a design whose operation may perhaps be better understood if we use the old term for self-induction and call it a machine of small electrical inertia combined with a large external inductance which provides the main electrical inertia of the system.

Of course there is a third plan which consists in combining plans 1 and 2, namely partially redesigning the field so as to reduce the self-induction by reducing the reluctance and number of turns while still employing a transformer to neutralize the mutual inductance between field and armature. This is probably the plan adopted in commercial apparatus containing the so-called transformer reactors, but it seems difficult to understand why, if the field design is to be modified at all, it is not better to go the whole way and design it so as not to need a transformer instead of only half-way when we still need a transformer.

In conclusion it is desirable to say something in justification of another point in the investigation. In my former paper "The Neutralized Welder," the arc was replaced by a constant voltage in formulating the differential equations. This procedure has been criticized in certain quarters but may be justified from Fig. 19 which shows arc voltage as a function of current and as a function of arc length. From this it will be seen that the voltage across the arc is almost exactly constant and independent of the current for the entire welding range of currents.

### ACKNOWLEDGMENT

The author is indebted for Fig. 19 to Messrs. E. C. Easton and F. B. Lucas to whom as well as to Professor A. R. Miller he wishes to extend his acknowledgment for assistance in the preparation of this paper.

# High-Frequency Arc Welding Generator

BY G. A. JOHNSTONE*

Member, A.I.E.E.

*Synopsis.—Extensive tests have demonstrated important advantages favoring the use of high frequency current for electric arc welding and have led to the development of a 900-cycle double induction generator of attractive characteristics and capable of supplying several different arcs at once. Some test results and a description of the high frequency generator are given.*

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EXPERIMENTS with induction generators operating at frequencies ranging from 500 to 9,000 cycles per second, have shown that currents of such relatively high frequencies have important advantages for use in metal arc welding and for other arc applications of heat. Experience with the inductor machines has shown them to have inherent characteristics that make them suitable for supplying current to electric arcs, and to give them both construction and operating advantages over d-c welding generators.

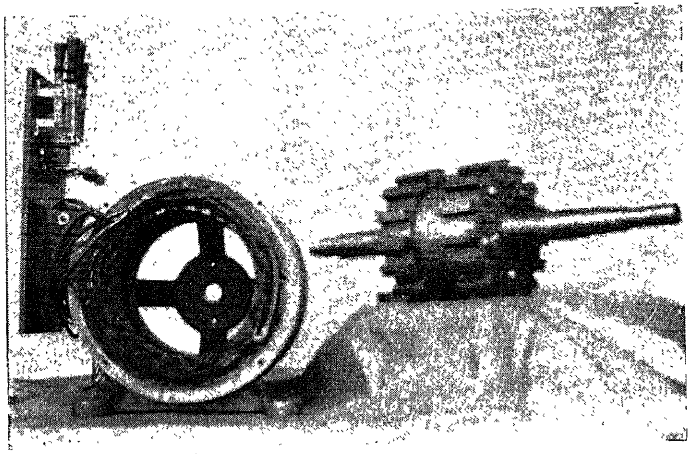

FIG. 1—A MULTIPLE-CIRCUIT 900-CYCLE 3,600-RPM, DOUBLE-CORE SINGLE-FIELD ARC WELDING GENERATOR

The generator as now commercially developed is of the double core type (see Fig. 1) designed to operate at 3,600 rpm to produce welding currents at a frequency of 900 cycles per second. The machine has the simplicity and the ruggedness of a squirrel cage motor, although the length of the air gap is almost twice that usually employed in an induction motor. The rotor teeth or poles are laminated, and the direction of rotation, of course, is optional. The relatively high speed enables direct connection to gasoline engines of similar speeds, resulting in portable sets, compact and light in weight.

The generator is self-excited, as indicated in Fig. 2, through a bridge connected full-wave rectifier. This generator circuit occupies 3 of the 60 stator teeth; the d-c field circuit is a single coil. The high reactance of the field coil at 900 cycles aids the operation of the rectifier and permits the use of the smallest number of units in series for the voltage needed. The higher frequency also lends itself to the use of condensers in connection with the excitation, in both the fields and load circuits. However, the results given in this article were obtained without condensers and with the field operated well below the saturation point. From the standpoint of arc welding still higher frequencies appear to have advantages, but a compromise was made at 900 cycles per second, partly to avoid the losses in core and rectifier at higher frequencies, and partly for structural reasons. Tests have shown the short circuit losses to check, or nearly equal, the total load copper losses plus the no load losses. Iron losses at higher frequencies also influenced the decision upon 900 cycles per second as the best operating frequency. As now designed, the generator efficiency is 80 per cent or higher for 200-amp and larger sizes. A 7½-hp motor is used for the 200-amp size, 10-hp for the 300-amp size.

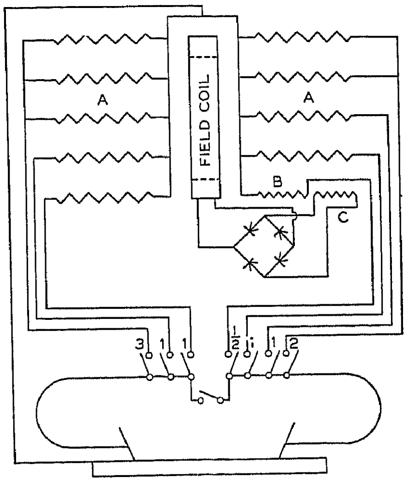

FIG. 2—SCHEMATIC DIAGRAM OF THE WINDINGS OF THE GENERATOR SHOWN IN FIG. 1

The 2 stator windings are divided into 10 welding circuits (*A* and *B*) and 1 field self-excitation circuit (*C*) involving a full-wave rectifier. Circuits may be switched according to number of circuits and welding current required

The multiplicity of welding circuits is noteworthy. By proper switching arrangement there may be as many operators as there are circuits (each circuit is independent; individual coils embrace only one pole, and there is but one coil per pole), or the circuits may be combined to give greater current capacity to fewer operators. The connection scheme shown in Fig. 2

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*Great Lakes Elec. Mfg. Co., Chicago, Ill.

*Presented at the A.I.E.E. Winter Convention, New York, N. Y., Jan. 23-27, 1933.*

would serve one operator with 2 arcs, or 2 operators each with 1 arc.

Volt-ampere curves for single circuits of this generator are shown in Fig. 3, where the dotted curves show values obtainable by field adjustment; however, as pointed out later, a field rheostat generally is unnecessary. As all the circuits have like characteristics and none is affected by the current in any other, the shape of the volt-ampere curve will be the same for all values of current obtained when several circuits are connected in multiple. For example, one main circuit may give 27½ amp short circuited, 26 amp at 25 volts, and 85 volts on open circuit; then if 8 main circuits are used in multiple the short circuit current will be 8 × 27½ = 220 amp, the load current 208 amp at 25 volts, and the open circuit voltage 85. This holds for any number of circuits.

The half circuit, it may be explained, uses half as many poles as a main circuit and has twice the number of turns per pole; its characteristics are exactly proportional to those of a main circuit. It is used to provide a smaller step in adjusting welding current to the value desired for any given work. The generator is flexible in this respect. It may be seen that, by simple changes in the switching, several circuits can be used in series for higher open circuit voltages, or separate combinations of circuits can have different voltages if not used in multiple. The characteristics of all such circuits will be similar and the short circuit ampere turns per pole for all will be the same for any given field strength.

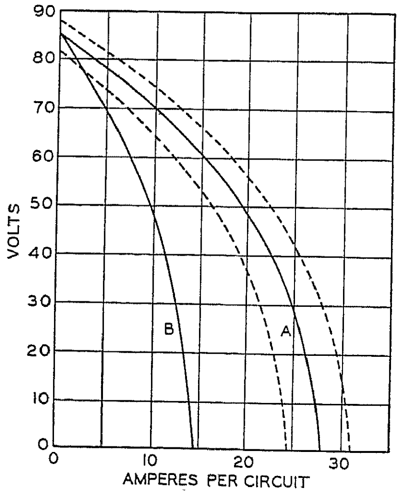

FIG. 3—CHARACTERISTICS OF 200-AMP 900-CYCLE ARC WELDING GENERATOR: (A) FULL CIRCUITS, (B) HALF CIRCUIT

These characteristics are entirely inherent in the generator; no external reactance or resistance is used. A set without field rheostat, even without instruments, is entirely practical from an operating standpoint. The switches afford all the control necessary and, being plainly marked either in amperes or units, indicate almost exactly the value of the current available for a certain setting.

In connection with the voltage regulation and the interrelation of circuits it is worth while to note that, although the statement that all circuits are independent of each other is true for all practical purposes, there is a small compounding effect. If, say, all but one of these circuits are shorted, the voltage on the open circuit will have a permanent rise of about 2 per cent with a 2 per cent drop in speed when the generator is self-excited; the field ammeter will show a corresponding permanent increase in field current. When the generator is separately excited, as it may be from any constant potential d-c source, the field ammeter will show a small upward kick of about the same magnitude as the permanent rise when self-excited, not more than 5 per cent of the maximum throw of the needle. This slight compounding effect is the only evidence of any inter-relation of the various circuits. When the machine is self-excited, the field current at open and short circuit is as shown in Fig. 4.

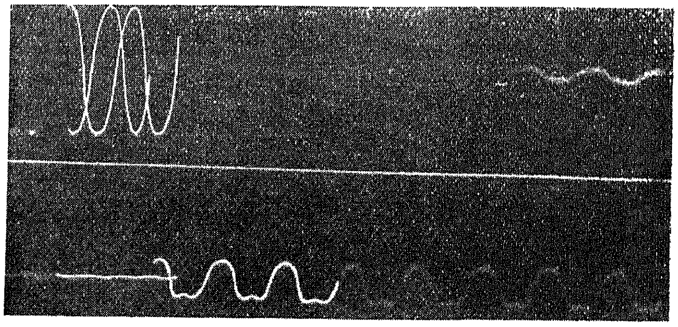

FIG. 4—LINE VOLTAGE AND FIELD CURRENT OF 900-CYCLE WELDING GENERATOR SELF-EXCITED THROUGH RECTIFIER; (LEFT) OPEN CIRCUIT; (RIGHT) SHORT CIRCUIT (PARTIALLY RETOUCHED)

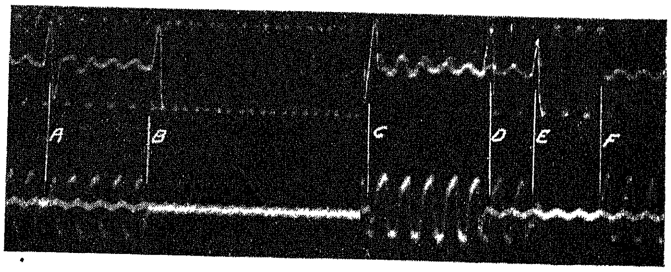

FIG. 5—VOLTAGE (UPPER) AND CURRENT (LOWER) CHARACTERISTICS OF 900-CYCLE WELDING GENERATOR ARISING FROM MAKE AND BREAK OF SHORT CIRCUITS

Momentary breaks at *A* and *C*; longer breaks at *B*, *D*, and *E*; make (circuit closed) at *F*

Fig. 5 shows that there are no surges of more than 10 per cent above normal in either voltage or current when short circuits were made and broken by wiping the welder's rod-holder quickly across the edge of the grounding base. It may be seen that the voltage and current curves show practically normal conditions immediately after the short circuit is broken or made.

Fig. 6 shows the voltage and current conditions while welding with a current of about 180 amp. These curves were taken with the same setting of the oscillograph as those in Fig. 5, and the same circuits of the generator were used for welding as were shorted in Fig. 5. The voltage curves of Figs. 5 and 6 were on a scale of 10 volts per mm. The open circuit voltage (Fig. 5 upper curve) has a value of approximately 100 volts maximum and the welding voltage (Fig. 6 upper curve) has a value of 43 volts maximum. These would be respectively 71 and 30 effective, assuming sine waves.

In Fig. 6 is shown a short circuit of the arc that lasted for 2½ cycles or about 1/360 sec, corresponding in time to 1/6 cycle of 60-cycle current. The current curve shows a slight increase during the short circuit and a noticeable change of shape, the front of the current wave during steady arc conditions being peaked, but during the short circuit the 5 crests have their peak at the tail of the wave. By the flattened crests of the current waves the short circuit is predicted a few cycles ahead of its actual occurrence. The zero points of the waves show no shift.

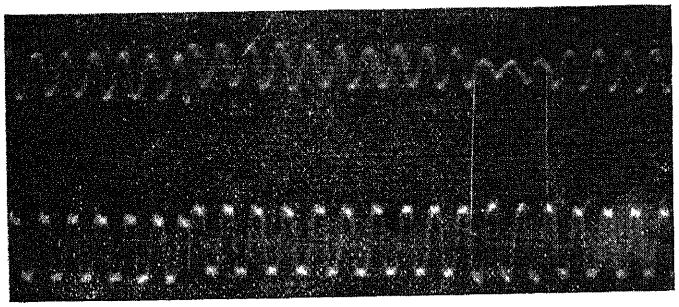

Fig. 6—Relations of Arc Voltage (Upper) and Current (Lower) for 900-Cycle 200-Amp Arc Welding Generator

Note the effects of short-circuiting the arc (toward the right)

The machine described makes a practical welding generator, with which metal arcs are easy to strike and hold, and good penetration is obtained. It is particularly good where the new heavy coated rods are used and in other work where reversed polarity of direct current is recommended. With a carbon torch this high frequency current also is useful. The arc projects so well away from the carbons that it is almost as handy to apply to the work as is a gas flame. In the case of the carbon arcs the no load voltage used is the same as for metal arcs. The carbon arcs operate at from 45 to 50 volts, with correspondingly lower current per circuit. It should be noted that this generator is operated at low open circuit voltage; comparable to d-c machines in this respect. Metal arcs are easy to strike and hold at from 65 to 70 volts. Arcs of smallest current values can be held successfully with open circuit voltages below 100.

Among the features of this high frequency generator that command attention are:

1. Multiple circuits for more than one operator; simple adjustment of circuits.
2. No transients that affect the welding operation.
3. Low open circuit voltage.
4. Inherent regulation, no external reactance or resistance required.
5. High efficiency.
6. Self-excitation, or optional separate excitation from any d-c source.
7. Weight and cost low; less than ½ the usual d-c machine; comparable to 60-cycle transformer equipments.
8. Three-phase loading of power lines as compared to single phase 60-cycle transformer sets.
9. Rugged construction of rotor; no windings; no commutator; no brush wear.
10. Optional direction of rotation.

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1. "Frequency Changer for A-C Arc Welding Machines," O. Neiss, *E.T.Z.*, **51**, pp. 311-313, Feb. 27, 1930.

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## Discussion

**F. Creedy:** Some years ago the writer carried out some work with the high frequency arc in Europe. The frequency used was only about 300, much less than that proposed by Mr. Johnstone but the operation of the arc was remarkably steady, just about equal to that of the d-c arc produced by the type of arc welder then in use. Of course since then the steadiness of the d-c machine has been a good deal increased. I can therefore confirm all that Mr. Johnstone says as to the advantages of high frequency for a-c welding.

A simple modification of the binary converter (described in the writer's paper *The Neutralized Welder*[1]) can be made which enables it to take three-phase, 50- or 60-cycle current at the stator terminals and deliver single-phase 300-360-cycle current at a couple of slip rings. All this may be done with a single machine having only one winding and not two on either member. Constructionally it is exactly like an ordinary induction motor and can use the same parts and only requires special punchings. It operates on 60 cycles at 3,600.

Regarding the subject broadly, an objection often made to these high frequency machines is that if we have to have rotating machinery anyhow we might as well use direct current. Which will win in the end is a matter of commercial competition.

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[1] A.I.E.E. Trans. Vol. 50, 1931, p. 662.

# Communication Requirements of Railroads

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*Synopsis.—Large railroad systems are complex organizations requiring extensive communication services to handle their special operating problems and to enable them adequately to reach and serve the public. Brief descriptions of the major requirements for circuits, switchboards, radio, carrier, plant and apparatus are given.*

It is the purpose of this paper to outline briefly the communication requirements of a typical large American steam railroad system.

Due to limitations of space, statements will be made which apply more or less generally but are subject to detailed variations and exceptions.

A modern railroad system is a vast and complex business with tens of thousands of employees and thousands of miles of far flung lines spanning one-half and more of our continent. To function efficiently such a large business must be highly organized with a resulting division of labor into allied groups. Whether the organization be along military or departmental lines, there have been evolved departments which are generally similar on practically all roads, as indicated in the following list:

Executive
Transportation
Traffic
Engineering
Motive Power
Car
Accounting
Legal
Treasury
Purchase and Stores
Real Estate and Tax
Signal
Electrical
Claim
Telephone and Telegraph
Police
Safety

From the above it may be presumed that there are many contacts between the railroad and the public it serves, as well as between departments, necessitating comprehensive and continuous communication service.

### TELEPHONE AND TELEGRAPH SERVICES

*Dispatching.* A regular train is one authorized by time table schedule which means that its leaving time and passing time at each station is shown in its schedule and that the train shall not pass any designated station before the designated time. If it is desired to run a train ahead of time, it is run as an extra or on the schedule of a preceding train. If no other trains were operated than those shown in the time table and if these were always on time, a railroad could be run by the time table. However, there are many extra trains operated that are not scheduled and the scheduled trains will, at times, run late due to various causes. It is therefore necessary to have other means than the time table to insure the prompt, safe movement of trains. This need has brought into being a very highly developed technique of train direction known as dispatching.

The passage of each train by a station is reported to a dispatcher located at division headquarters. It is the duty of the dispatcher to arrange for the movement of the trains around and past each other. To do this, he requires dispatching circuits, either telephone or telegraph or both. These circuits are connected into each station in his territory. If a circuit is operated telegraphically, calling of the stations is by Morse code. If the circuit is operated telephonically, calling is by means of a key which sends out coded impulses which operate a device known as a selector at the station called. The operation of the selector rings a bell and sends a tone back to the dispatcher, indicating that the bell has rung. Each station is provided with suitable telephone equipment to answer calls. Such equipment is standard, but of a more or less special type developed for the use of this service.

The dispatcher is provided with a loud speaker that is always connected to the dispatching circuit and if any station desires to talk with him, the station operator simply connects his telephone to the line and proceeds to talk. In very congested territories where many trains are involved, it is desirable also to provide the stations with loud speakers. In this case the dispatcher is saved the time of calling, as he merely announces the name or call of the station desired and proceeds with the message. Dispatching circuits vary in length from 15 mile terminal circuits to about 600 or 700 miles depending on the density of traffic. They probably average 200 miles. The number of stations connected thereto also varies widely from perhaps 15 to more than 100 with an average between 40 and 50.

Dispatching circuits are the most important on the railroad. The use of the telephone is considered preferable to the telegraph and each year sees an increase in the former at the expense of the latter. At the present time, nearly all main line and a majority of all mileage is dispatched by telephone. The circuits are usually composed of No. 9 AWG copper, although in some cases where territories are long or weather conditions severe, No. 6 AWG copper is used. These circuits are normally designed with a transmission equivalent of not over 20 decibels with a maximum of 25 decibels to the dispatcher. Often the dispatcher is located at some point other than the terminal, in which case the overall equivalent may be as large as 30 decibels.

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*Block and Siding Communication.* To increase safety of operation, separation between trains in distance is maintained. This is done by dividing the track in sections called blocks averaging 8 to 10 miles long. Under one system known as the "absolute" but one train is permitted in any one block at a given time; under a more generally used system known as the "absolute—permissive" not more than one passenger train may occupy a block at any one time, but a freight train is permitted to follow another freight train into a block, first being warned by signal or special instruction that the block is occupied and to proceed with caution prepared to stop. The signalman at the end of each block keeps a record of all train movements in and out of the block on either side of his station. Upon the approach of a train he consults his record and if the block is clear, communicates with the station in advance. If the advance station finds the block clear he displays a stop signal against opposing trains and advises the first station that the block is clear.

The circuits used to communicate between the two stations may be either telegraph or telephone. Usually only the two stations concerned are connected to the circuit. If it is a telephone circuit, it is simplexed and the derived telegraph circuit is used as a way station telegraph circuit. As block circuits are usually short, transmission considerations do not normally govern the choice of wire, which may be either No. 8 BWG iron or No. 9 AWG copper, depending upon which is considered the more economical. If simplexed, copper is generally preferable. The block circuit which is so intimately connected with train operation is one of the more important circuits required by the railroad.

In automatic signal territory, especially with multiple tracks, manual blocking is not required except when trains are operated against traffic.

When a train takes a siding, the conductor must report to the block operator that the train is clear of the main track so that other trains may be advanced through the block without delay. Telephone circuits known as siding lines are often strung to the switch at the end of a siding to permit the conductor to call in and clear the train without his having to walk back the full length of the train, which would require considerable time in the case of a long freight train. These lines are also used before the train leaves the siding, the conductor calling up the block operator and obtaining the necessary permission to enter the block. The telephone instrument is housed in a small box mounted on a pole or in a booth. At times the siding lines are not provided and the telephone is connected directly to either the block or dispatching line.

*Telegraph Way Circuits and Telephone Message Circuits.* Where dispatching is by telegraph a second telegraph circuit, cut into the same stations as the dispatching circuit and often into additional stations, is required for handling the general divisional business and as an auxiliary circuit for the dispatcher.

Where dispatching is by telephone and an auxiliary telephone message circuit has not been provided, a telegraph way wire similar to the one described in the preceding paragraph and for the same purposes is generally available. Where a block circuit is used, this way wire is obtained from the simplex on the block telephone wires; otherwise, it is the ordinary way station telegraph wire.

Where traffic conditions warrant, a message telephone circuit is provided. This is like the dispatchers circuit in its physical makeup, except that it usually has drops to freight houses, depots and other places not connected to the dispatcher's circuit. Generally it is terminated in P.B.X.'s at each end, and the latter do the ringing. Its selectors are set with the same codes as the dispatchers circuit so that in case the latter fails, sections of the message circuit may be used to make the dispatching circuit good or the entire circuit may be turned over to the dispatcher. The way telegraph or message circuits are normally required in the transaction of local business of the division. The car distributor uses it extensively and traffic matters concerning rates, routings, reservations, etc., are handled with the division traffic agents. The division engineer uses it as a prompt means of conferring with and issuing instructions to his section and bridge foremen when necessary. In addition, many telegrams on various matters pass over this circuit. On very busy divisions, two such circuits may be required, due to the heavy volume of message traffic.

*Long Distance Telephone Service.* Various divisions are grouped under an operating head known as a general manager or general superintendent. Long distance telephone service connecting these division offices with general headquarters is obtained by the use of a phantom on the dispatching and message circuits where the divisions under control radiate from the operating headquarters. Otherwise, additional circuits are constructed or telephone repeaters provided for existing derived circuits.

Service from the executive general headquarters to general operating and traffic officers is provided by means of trunks between strategic telephone switching points.

Telephone repeaters, and entrance cable loading may be necessary to give satisfactory over-all transmission. As terminal losses on calls to local points, city ticket offices, etc., will usually equal or exceed 5 decibels, the trunk equivalent between any two points should not exceed 20 decibels.

*Private Branch Exchanges.* At a large terminal or general headquarters, there may be hundreds of commercial telephones serving the various railroad offices. These offices have numerous contacts with each other and the public. To provide the usual direct business telephone would require a huge directory listing in the telephone company's directory and place on the public the burden of searching for the particular party desired who in many cases is not known. The arrangement, as a matter of fact, would be impracticable. The need for convenient and economical distribution of such calls with a minimum of inconvenience to the public, has been met by the installation of private branch exchange switchboards. A private branch exchange switchboard is usually located in one of the railroad buildings near the center of the telephones connected to it. The local calls from one department to another are, of course, routed through this board. Sufficient central office trunks are provided to handle the traffic to and from the public. The board is manned by trained operators, on the railroad's payroll, who are familiar with the practises of the various departments served and can properly distribute the calls to the persons desired.

The private branch exchange is also used to connect the railroad's long distance telephone lines with the local terminals.

Switchboards may be either owned by the railroad or rented from the commercial companies. In the latter case connections may be established between the long distance lines and the plant of the telephone company. The P.B.X. may be either manual or semi-automatic. Semi-automatic operation usually provides for incoming city and long distance manual service and automatic or dial outgoing city and station to station service.

In some cases, it is preferable to install more than one P.B.X. within the terminal territory to take care of specialized traffic or in situations where telephones are so scattered as to make the provision of direct lines too expensive. Generally the larger city ticket offices and freight terminals are provided with P.B.X.'s of their own and are so listed in the directory. These might be handled from a central board, but in practise it is found that since the traffic is of a specialized nature and almost exclusively with the public, that greater efficiency can be obtained from a separate board. This applies only to the larger locations. At smaller places a single central board is usually better.

In executive offices where a special secretarial service is desired, small auxiliary boards connected by tie lines to the main P.B.X. are frequently an advantage.

An outlying yard several miles from the central board is a good example of specialized service requirements. The traffic in this case is largely local station to station and of a more or less special kind. To provide direct lines from the main board would often involve an expensive underground and aerial cable, whereas the separate board would be less costly.

*Pullman Reservation and Information Bureaus.* These two services require special communication arrangements.

At the Pullman reservation bureau, each car has associated with it a diagram card, upon which is indicated the space available in the car. The current month diagrams, one for each car and for each day of the month, are grouped by trains in a rack mounted on a table. The rack is built as high as a person can conveniently reach from a sitting position and of such length as to accommodate the necessary number of cars. Along the table on each side are seated from possibly 4 or 5 to as many as 40 diagram clerks, depending upon the number of sleeping car lines operating through the terminal. Each clerk has a telephone and by means of keys can connect it to any one of a number of lines appearing in the table shelf in front of the clerk. Associated with the table is an automatic telephone exchange from which extend lines to the ticket sellers in the depots, city ticket offices and hotel ticket offices. A patron desiring a section between two points on the railroad makes his wishes known to the ticket seller, who, by means of his telephone, dials the particular section of the diagram rack in which he knows the diagrams for the particular train are located. A signal lamp will light in front of several clerks facing these diagrams, one of whom will answer and give the desired space. It is to be noted that no public telephones are connected to this unit, nor does the public have direct access to it.

In addition to the above unit, another somewhat similar unit is sometimes provided known as the public reservation. The public reservation is provided with direct trunks from the telephone company's central office and listed separately under the trunk number in the directory. Incoming calls may be distributed by means of a P.B.X. to the clerks, or the lines may be multipled through the table with lamp signals in front of all or groups of operators so that if one is busy, others may answer. Pullman space reservations requested by patrons over the telephone are made at this unit. The clerk answering a call would either leave the table, go to the diagram rack and secure the space, or transfer his telephone to a line connected to the automatic unit serving the diagram board, dial the particular section desired and secure the space from the diagram clerk, then inform the patron.

The information bureau is provided with trunks from the telephone company's central office and given a separate listing in the directory. The incoming calls may be received at a switchboard and distributed to the information clerks or the lines may be multiplied through the table with answering lamps appearing in all or any number of positions. Tie lines are provided to the diagram unit so that the information clerks may secure Pullman reservations direct when asked for in addition to train information.

Some railroads consolidate the diagram and public reservation units, others combine the public reservation and information bureaus and some feel that separate units are more desirable. Generally it is believed that a separate diagram unit and a consolidated public reservation-information unit is preferable.

*Centralized Reconsigning and Tracing Bureaus.* Railroad service has become so reliable that merchants have in many cases reduced stock to a very small percentage of that formerly carried depending on scheduled delivery of orders on time. This has naturally resulted in a much increased concern as to the freight movement, some shippers requesting information as to exact time their cars leave terminals and pass intermediate points enroute. This has resulted in a considerable increase in car tracing. The greatly increased movement of perishable freight has also resulted in a large increase in reconsignments or diversions. Entire train loads of fruit, for example, may be started and consigned to some point. The shippers then proceed to dispose of the freight while in transit and in a short time the railroad will receive telegrams reconsigning or diverting the cars in the train.

Modern trend is toward a centralization of tracing and reconsigning activities into central points either for the system or by regions embracing fairly large portions say one-fourth of the system mileage that is closely allied.

When through freight trains leave their initial terminals, the number, consignee or contents and destination of each car, the time of leaving, the time it passes each important terminal, and the time it reaches its destination or is transferred to another railroad is telephoned or telegraphed to the central trace bureau. At this point the cars are booked by a number system so that they can be readily located. All requests for tracing or orders for reconsignment are directed to the bureau, the latter from its records can usually answer any tracing request at once and, knowing the location of cars in transit, effect a reconsignment or diversion with a minimum of delay.

Practises vary as to the number of trains handled through trace bureaus, some railroads booking practically all through freight trains while others book only the higher class trains moving perishable freight.

In a regional plan existing telephone and telegraph facilities can usually handle the transmission of the necessary information through the regular channels. Frequently idle telephone circuits can be utilized during the night.

In a central system plan special telegraph circuits equipped with printers will usually be provided. Generally the demand will exceed existing available facilities necessitating the construction of additional lines at considerable expense.

*Morse Telegraph Circuits.* In addition to the way or message telegraph circuits previously mentioned, a network of through telegraph circuits is required. Upon these are handled a great variety of messages, daily situation reports, Pullman reservations, car tracers, reconsignments and diversions, car home routes, special passenger equipment movements and many miscellaneous messages of a general nature. The number of such messages on a large system will average from 12,000,000 to 36,000,000 or more per year.

In addition to the way wires and depending upon the particular type of organization, other circuits may be set up between the division headquarters and the general superintendent's headquarters, between the latter and important outlying terminals and general operating headquarters. General operating headquarters if more than one will usually have direct service with each other, also to the executive headquarters.

Many of these circuits are derived from simplexing or compositing telephone circuits; others are strung as single wires.

When hand sending is employed they may be operated single where transmission is one way at a time; duplex where two messages are sent simultaneously, one in each direction, or quadruplex where four messages are sent simultaneously, two in each direction. Comparatively few of these circuits are operated either single or quadruplex, the great majority being operated duplex.

When the traffic becomes sufficiently heavy to warrant their use, printing telegraph machines are used. As in the case of hand sending they may be operated single (it is called in this case simplex), duplex or multiplex. In the latter case, as many as four messages can be sent in each direction at a time. The printer sending operator types the message on a key board similar to that of an ordinary typewriter and the message is automatically typed at the other end by the receiving machine.

In the longer circuits telegraph repeaters appropriate to the type of circuit are required at intervals varying with the weather conditions and resistance of the wire from 150 to 300 miles.

In the larger terminal telegraph offices, belt conveyors along the operating tables for collecting incoming messages are desirable as they speed up the movement of messages and usually effect savings in messenger expense. Where these larger offices serve general office buildings, a pneumatic tube delivery and pick up service is desirable. Where tubes are installed the conveyor belt should be arranged, if practicable, to deposit the messages at the tube center so that they can be immediately dispatched. Tube systems are also very efficient for the handling of inter-office mail in the building.

*Local Printer and Announcing Circuits.* In addition to their use in general telegraph message service, printers are required in a number of local and short wire services.

In the new type car retarder yards as soon as a train pulls in the receiving yard the waybills are sent to the yard office usually by pneumatic tube. The yard clerks immediately start preparing a switching list indicating the manner in which the train will be switched to the classification yard. They do this on printers which simultaneously type the list in the switching towers. As the train is slowly pushed over the hump the tower operators divert the cars into the various tracks of the classification yard in accordance with the list. By the use of the printers, switching can start almost immediately, otherwise it would be necessary to wait until the list has been completed and copies sent to the towers.

A loud speaking telephone system is also provided between the yard office, hump and switch towers. This is required to provide a means of instantaneous intercommunication so that corrections and changes can be quickly made and emergency information passed between offices relative to the handling and disposition of the cars.

Ready use is found for printers at terminals for the transmission of various sorts of information such as orders to coach yards concerning the arrangement, make up and changing of passenger equipment, the arrival of freight to downtown offices, etc.

At large passenger stations, arrival of incoming trains is reported from outlying towers to the incoming bulletin board, information bureau, mail room, station master, baggage room, telegraph office, taxi cab headquarters, etc. This is done either by printers or telautograph.

In connection with or in addition to this circuit there is provided in some instances a loud speaking or public address system to announce to the waiting public the arrival and departure of trains. In lieu thereof the information is sometimes thrown on a screen by means of a projection machine.

*Time Service.* It is essential that accurate time be maintained on a railroad. At dispatcher's offices, yards and terminals accurate clocks are provided known as standard clocks with which trainmen compare their watches before starting on their tours of duty. Each day at noon eastern standard time, usually through arrangement with a commercial telegraph company, U. S. Naval Observatory time is sent over the telephone and telegraph networks of railroads to all stations. Formerly this was sent exclusively by telegraph, but at present both telephone and telegraph are used. The standard clocks are compared with the time signals and the seconds fast or slow are posted at the clock. When clocks vary more than 10 seconds, they are set and regulated.

*Acoustical Treatment.* Accuracy and efficiency in dispatching and telegraph offices, telephone exchanges, Pullman reservation and information bureaus are promoted when the room noise is lowered by acoustical treatment of the ceilings. Material having a coefficient of absorption of 0.7 is usually satisfactory. Further reduction of noise can not usually be justified as the cost increases out of proportion to the benefits derived.

## RADIO AND CARRIER REQUIREMENTS

*Radio.* While there is a number of places where it is felt radio could be used advantageously in railroad service, its actual use has to date been rather limited.

In car retarder operation there is need for radio transmission from the hump to the locomotive pushing the train over the hump in order to direct movements, particularly during foggy or unusually stormy weather. Some trial installations have been made which indicated entirely satisfactory operation could be expected with necessary development.

On long freight trains there is need for communication from the caboose to the engine. Some of the advantages gained by the use of such communication are as follows:

Saving in coal.

In event of train separating crews are advised quickly of the trouble.

When flagmen are called in enginemen are quickly notified.

Standing trains can be quickly cut and reconnected for highway crossings.

Jammed and defective brakes can be cared for.

Orders missed by either end can be read to the other.

During fogs, heavy snows or rains, signals can be passed where otherwise impracticable.

Development work on radio sets for front to rear of train communication has been under way the past few years and sets are now available.

Some railroads have fleets of boats used in tug and ferry service in the harbors along the seaboard and on the Great Lakes. In dispatching these boats, especially the tugs, there is frequently need to communicate with the tug after it has left its pier due to changed conditions, such as late orders relative to picking up freight at intermediate points, cancellation or change of orders, etc. This communication can be obtained by means of radio but no use of it has been made by railroads to date.

A number of railroads has installed radio receiving sets for the entertainment of passengers. These sets are located in observation, club or lounge cars, some are provided with loud speakers, some with head sets. The use has been rather limited and installations have only been made on the higher class trains.

The matter of commercial radio telephone communication to passengers on trains has received some attention but it is felt it is essentially a matter for consideration by commercial companies.

*Carrier.* Carrier telegraph or telephone systems have not been used on railroad lines in the United States on account of cost considerations. The Canadian railroads, however, have installed an extensive circuit mileage of carrier.

## OUTSIDE PLANT REQUIREMENTS

The factors underlying the design of communication pole lines of railroads are somewhat different than those involved in the design of lines of commercial companies. The latter usually have alternate routes in case of failure while this is almost always the exception with a railroad. Then, too, the railroad communication pole line ordinarily carries the automatic signal wires, the failure of which causes serious interference with train operation. For these reasons, railroad pole lines require a higher strength factor than the commercial lines. The problem is essentially one of engineering design. The proper loading assumptions based upon the maximum velocity of wind and coating of ice for the territory involved are determined. From these the required number and size of poles per mile for any desired factor of safety may be determined. The Telegraph and Telephone Section of the American Railway Association in its basic rules and pole tables recommends a minimum factor of safety of two.

## CONCLUSION

From the above it may be noted that the communication requirements on a railroad are extensive and exacting.

In order to construct, maintain and operate such a plant efficiently a separate communication department is required, provided with the necessary technical engineers, construction men, wire chiefs, traffic men, etc.

The communication departments of the railways of the United States, Canada and Mexico are organized under the American Railway Association into a Telegraph and Telephone Section. This body, through its committees, prepares and promulgates standards for construction, maintenance and operation. By its work great strides have been made in standardization of railroad practises with ensuing economy.

Looking to the future, the ideal to which the railroad communication service should strive is uninterrupted and prompt telephone and/or telegraph service from any point on the system to any other point.

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## Discussion

For discussion of this paper see page 294.

# Communication System on the Pennsylvania Railroad

BY I. C. FORSHEE*
Associate, A.I.E.E.

*Synopsis.—The paper gives a description of the communication services required for operation of the Pennsylvania Railroad and for the convenience of its patrons, also a description of the company-owned outside plant required to provide the service, together with tabulations showing the magnitude of some classes of business handled and plant involved.*

## GENERAL

THE magnitude and importance of the communication system required for the safe and efficient operation of a large railroad system are seldom appreciated by those not closely in touch with it.

Unlike most railroad companies in this country, the Pennsylvania owns, maintains and operates its pole lines, conduit lines and cable system, and where wires or cables of commercial telegraph or telephone companies are on the railroad right-of-way, it is on a rental basis.

This paper will outline briefly the principal classes of service involved and the facilities required to provide it on the Pennsylvania Railroad.

## HISTORICAL

The development of the American railroads has been concurrent with that of the telegraph, telephone, telegraph printer and radio, and the Pennsylvania has been a pioneer in the experimental development and application of each form of communication to its use in railroad operation.

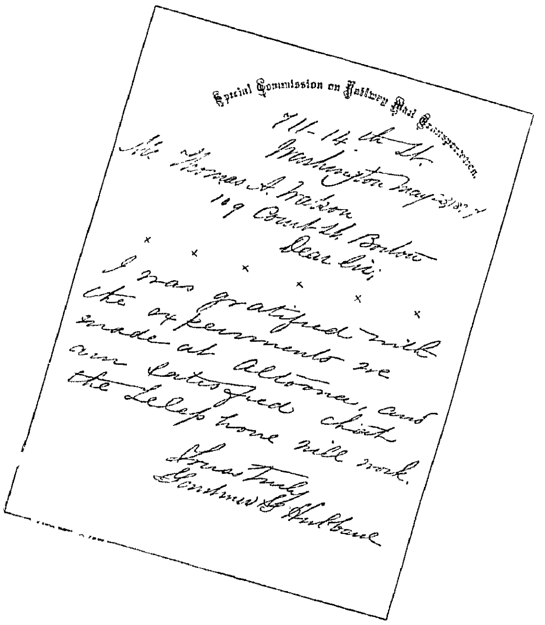
The Morse telegraph was introduced about 1844; the Pennsylvania Railroad was chartered in 1846; the first time telegraphy was used to dispatch trains was in 1851, and the Pennsylvania was among the first to make use of this new means of communication.

The use of the telephone in the early days of its development, as applied to railroad work, is evidenced by an interesting letter from Mr. G. G. Hubbard, an associate of Alexander Graham Bell, to his assistant, Mr. Thomas A. Watson, regarding the use of the telephone in the shops at Altoona, Pa., May 23, 1877. See Fig. 1. This marked the first trial and use of the telephone by any railroad, and was the beginning of the system which is now probably the largest privately operated system used by any railroad in the world.

Likewise the merits of the telegraph printer, telautograph, telephone selectors for train dispatching and message circuits, loading coils for cable, and telephone repeaters for long distance service were recognized in the early days of their development, and installations of each were made at an early date.

## COMMUNICATION SERVICES

*Train Operation.* The most important class of communication service in railroad operation is the privately owned train dispatching system which is now telephone operated on 96 per cent of the Pennsylvania's mileage. The small percentage of telegraph dispatching remaining is on branch lines where the traffic is relatively light. The development and perfection of the telephone selector has made this possible and practicable. In some sections the telegraph is still retained for service in the event the telephone fails, but is seldom used otherwise. On other divisions no telegraph equipment is used at all for either dispatching or message work, both being handled by telephone.



Special Commission on Railway Mail Transportation.
711-14th St.
Washington May 23 1877
Mr. Thomas A. Watson
109 Court St. Boston
Dear Sir;
× × × × × ×
I was gratified with the experiments we made at Altoona, and am satisfied that the telephone will work.
Yours Truly
Gardiner G. Hubbard

Courtesy—American Telephone and Telegraph Co.

FIG. 1—PORTION OF LETTER FROM G. G. HUBBARD TO T. A. WATSON, MAY 23, 1877, REGARDING TESTS WITH TELEPHONE AT ALTOONA SHOPS

The dispatcher, normally located at division headquarters, is provided with selector calling keys which enable him to call selectively any one of the many telephones at the interlocking or block stations on the division or section over which he is dispatching trains. The usual arrangement at the dispatcher's office also includes a loud speaker, with provision for a head receiver if desired, and a breast transmitter with foot

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*Pennsylvania Railroad Co., Philadelphia, Pa.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

switch or hand key for transmitter cut out. The receiver is always on the line so that any party on the line can get the dispatcher immediately without signaling if the line is not busy.

The exact time the different trains, both freight and passenger, pass the different interlocking and block stations is reported to the dispatcher immediately and he records this on his train sheet.

When everything is working normally, the dispatcher has little to cause him worry, but trouble which changes the spacing of trains, diversions from their normal routes, running against current of traffic, changes in meeting and passing points and many other special conditions require a clear head and quick and accurate decisions; the quality of the transmission to the end of his circuit must be within certain limits so that there is no misunderstanding of orders or information given. Train orders are always repeated back and must be correct before they are put into effect.

The dispatching circuit is used exclusively for that purpose and in event of trouble on it, other circuits are taken to make it good. In the event of storm prostration or other emergency causing interruption of service, the dispatching circuits are always the first to be restored.

Interlocking and block stations are usually equipped with a switching cabinet mounted on a table in front of the operator. All the lines entering such an office for service terminate in this cabinet equipped with keys, jacks and signals so that the local telephone set may be connected to any line by merely pushing a key. Jacks and patching cords are provided so that any line may be connected to any other line in the panel. Test and patch panels also are provided at certain points, where all lines would be available for testing and patching.

Block circuits, which are local circuits extending in each direction between adjacent block and interlocking stations, are used by the block operators to pass information regarding approaching and passing trains, and are considered about as important as the dispatching circuits from an operating standpoint.

Signal bridge telephones are installed in the familiar shelter boxes at practically all signal bridges along the main line and at each end of passing sidings, and are connected to circuits to adjacent block or interlocking stations. These circuits are used by conductors and enginemen of trains in ascertaining from the signalman the condition of the block and in obtaining permission from him to enter the main track from a siding or branch line track where there is no block or interlocking signal to govern.

*Telephone Message.* Telephone message circuits which correspond closely to the dispatching circuits in their characteristics, are generally used for handling intra divisional messages. They are usually equipped with selectors and extend to the same points for service as the dispatching circuits, and in some instances also connect to stations.

In case of trouble on the dispatching circuits between certain points, the message circuit is broken at the patch panels at each end of the section in trouble and is used to make the dispatch circuit good until the trouble is cleared on the dispatching circuit.

The message circuit usually is phantomed with the dispatching circuit to provide additional telephone tie or trunk circuits, and they are simplexed or composited for additional telegraph or printer circuits between the different division headquarters.

*Telegraph and Printer.* Message and report business between the general office, regional and divisional headquarters is handled largely by Morse and printers.

A special type of report used in car tracing and reconsignments is important in connection with certain classes of freight shipments and is known as a passing or consist report. These are sent from certain important yards to car trace bureaus at regional headquarters and show the car numbers, lading, consignee, destination, date and time of passing certain points for important freight enroute. Many of these reports are handled on the printers.

Both Morse and printers are operated duplex on the through service, using telegraph repeaters when and where required.

Commercial telegraph business for the convenience of the public is handled at practically all stations, through arrangements with the commercial telegraph companies.

*Emergency.* In territory where the circuits are all in cable, the only access to them for emergency service between the stations and interlocking or block stations is where they are terminated on binding posts in the telephone shelter boxes. This provides for connections from along the track to block and interlocking stations and other points on the system. These circuits are independent of the regular block or signal bridge circuits and generally terminate in the block office switching cabinet where they may be switched to other circuits depending upon nature of service desired. It is considered necessary to provide this service which cannot be interrupted by any other telephones in the block, and has proved very efficient in emergencies.

Another class of emergency service which is used in event of prostration of lines between general office and regional headquarters or between division headquarters includes the tie lines for telegraph or telephone service to the adjacent offices of the commercial telegraph and telephone companies. These arrangements make it possible to establish connections to the distant points without delay, providing that the commercial lines are not similarly affected.

*Time Service.* One very important detail in connection with train operation is correct time which is available at all points where trains are operated and reported. This requires clocks with a relatively high degree of accuracy. In some places the trains are on such short headway that the passing time report includes the seconds as well as the hour and minute.

To insure that the clocks are all in step, official time signals from the U.S. Government Naval Observatory at Washington, D.C., are sent out on the system twice daily, at noon and at midnight, and the clocks are set accordingly. Special circuits for telephone and Morse are set up for this purpose.

*Telephone Exchanges.* Private branch exchanges for intercommunicating service and for service to and from the public are installed as shown in Fig. 2. In size these vary from the small one-position manually operated board to the largest manual board on the system at the general office, Philadelphia. This is a 23-position board equipped with 1,240 telephones, 38 long-distance trunks, 170 tie lines and 106 trunk lines to the telephone company's central office.

The trend is toward machine switching equipment, replacing the manually operated boards, as is evidenced by the changes which have been made in many of the most important exchanges on the system, including Chicago, Pittsburgh, Harrisburg and New York. A machine switching exchange is being installed in the new station at Philadelphia which will consolidate the 23-position manual exchange, an 8-position manual board, a 100-line automatic and several smaller exchanges. This type of exchange provides dial equipment for all intercommunicating service which is available 24 hours per day for any sudden emergency which would create a peak load, an advantage which is readily appreciated, and provision is made for tie line dialing for calls to many of the railroad exchanges quite widely separated. Outgoing calls to the Bell system also may be dialed or restricted as desired. Incoming calls from the public and the longer trunk line calls will be handled manually. The trunk calls are handled manually as more efficient use can thus be made of this part of the plant which represents an appreciable investment than if handled on a dial basis. Preferential and emergency calls can thus be made.

The consolidation of exchanges in the larger centers has been under way for a number of years in the interest of economy, improved service, better transmission and also for the benefit of the public, as it simplifies the directory listing. Evidence of this trend is indicated by the reduction of the number of exchanges on the system from 192 in 1925 to 124 in 1932 prior to the consolidation at Philadelphia.

A modern machine switching private branch exchange is installed in New York. There are about 600 subscribers' lines, 60 trunks and tie lines to other P.R.R. exchanges, and 80 trunks to the Bell central office. This exchange provides telephone service for the railroad in the New York district where formerly there were several exchanges, each with a different directory listing.

*Train Information.* A special class of telephone service and equipment is provided at certain of the larger stations to furnish information to the public regarding passenger train service, such as the arrival and departure of trains, train connections, through service over foreign lines, rates for transportation, Pullman fares and so forth. In the Pennsylvania station New York twelve operators are at times kept busy answering such inquiries.

Provision is made for a transfer of incoming calls to the regular private branch exchange or to the Pullman reservation equipment when so requested by the calling party. In case a call is made originally to the main private branch exchange and train information is desired, the call may be transferred.

Telautographs and printers are used in a number of the larger stations for the purpose of giving information regarding trains. This information is used by the attendants at such locations as information desks, local block and interlocking stations, station master's office, bulletin boards, baggage offices incoming and outgoing and mail rooms. The principal information so handled is regarding time of arrival and departure of trains, track on which they will arrive and so forth, and is transmitted from the local train director's office or the terminal block or interlocking stations. This is essential information for the public. They also serve for the proper receipt and dispatch of baggage, express and mails. Their importance is probably greatest during the holiday rushes, vacation periods, during storms when train delays are imminent and inquiries from the public are most numerous, also during special events when extra or special trains are provided.

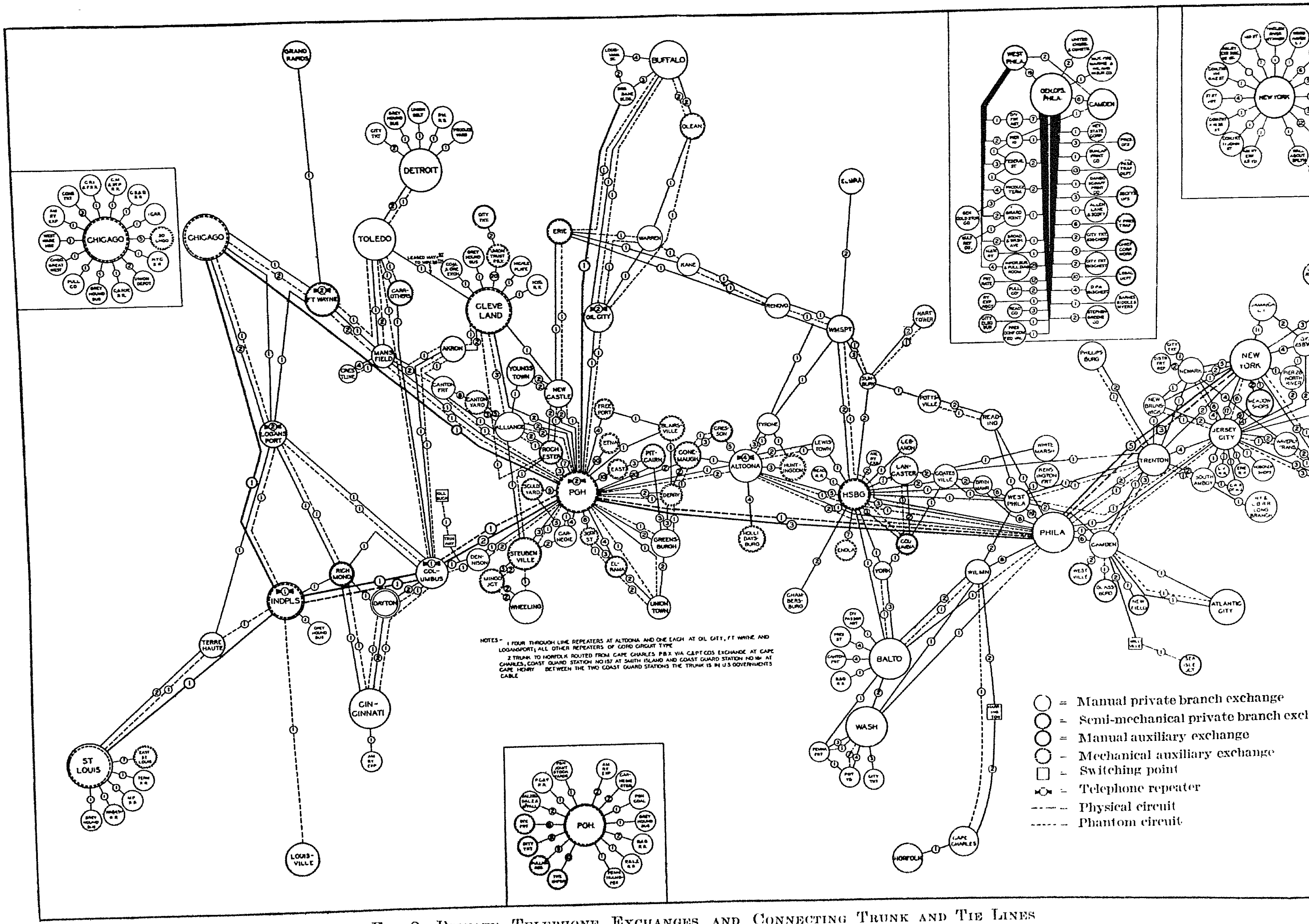
*Pullman Reservations.* In the larger stations such as Philadelphia, Chicago, Pittsburgh and New York the Pullman reservations are all made by telephone from the ticket windows in the stations, uptown ticket offices or consolidated ticket offices to the reservation room. The diagrams for all trains for the current date and for advance reservation are available in front of operators, provided with special equipment. Different sections of the railroad and different foreign line connections are handled at different reservation desks.

The installation in the Pennsylvania station New York shown in Fig. 3 is the largest and most modern, and is the result of experience over a number of years.

Ticket windows in the stations and other ticket offices in the city are provided with dial telephones connected directly with this system so that the ticket seller can call the particular section or table handling the diagrams for the trains desired. Incoming calls from the city or public are received on a special manual board where an operator will question the calling party as to reservation desired, and then will switch the call to the proper table to handle that class of reservation.

Many reservations are made by telegraph from out of town points. To handle this business without delay a pneumatic tube is used between this office and the railroad telegraph office. There is sufficient reservation business between Philadelphia and New York to assign one telephone trunk exclusively for this business.

*Messages to and from Passengers Enroute.* Through arrangements with the commercial telegraph companies,



NOTES— 1 FOUR THROUGH LINE REPEATERS AT ALTOONA AND ONE EACH AT OIL CITY, FT WAYNE AND LOGANSPORT; ALL OTHER REPEATERS OF CORD CIRCUIT TYPE

2 TRUNK TO NORFOLK ROUTED FROM CAPE CHARLES PBX VIA C.&P.T.CO'S EXCHANGE AT CAPE CHARLES, COAST GUARD STATION NO 157 AT SMITH ISLAND AND COAST GUARD STATION NO 161 AT CAPE HENRY BETWEEN THE TWO COAST GUARD STATIONS THE TRUNK IS IN U.S GOVERNMENT'S CABLE

Fig. 2—Private Telephone Exchanges and Connecting Trunk and Tie Lines

messages to passengers enroute on trains may be addressed to the individual in care of the conductor of the particular train. Such messages would be handed to the train conductor at a scheduled stop of the train, and he would then page the train for the party addressed.

Likewise messages from the passengers enroute may be transmitted from practically all scheduled train stops.

*Telephones on Limited Trains.* For the convenience of the traveler on certain of the through trains, telephones are provided in the observation or club cars while in the terminals. This telephone is connected through special jacks on the car, plug and portable cord to the station platform jacks and to the railroad exchange from which connection may be made to the party desired. This is a convenience that is really appreciated by one who may have forgotten some important matter in the rush to catch the train.

*Commercial Telephones in Stations.* For the convenience of the public, commercial telephones are provided in practically every station. These are connected directly to the Telephone company's system and, unless an attendant is present, are of the coin box type.

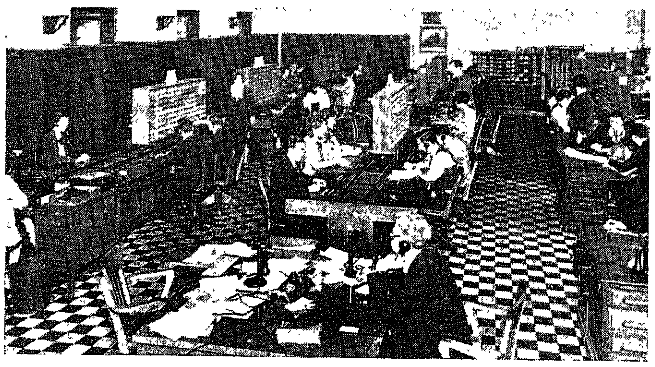


Fig. 3—Pullman Reservation Room New York

*Power Director.* A very complete telephone system is provided for the efficient operation of the power system in connection with the electrification, and is independent of the other facilities mentioned. A chief power director will be located at Philadelphia who will coordinate the work of the different power directors located at the division headquarters of the sections electrified; as at New York, Jersey City, Philadelphia and Baltimore.

The system includes selector telephone equipment on the circuits from each power director to the different substations and adjacent block and interlocking stations where control equipment is located; direct lines between the power directors and from the power directors to the train dispatchers on the divisions over which each is responsible for service; direct lines from the power directors to the power company in each territory involved; direct lines from the power directors and from the chief power director to the railroad exchange in that district; and patrol circuits from the shelter boxes at the signal bridges along the railroad to the power directors. These circuits of necessity all have a high grade of transmission and are all in cables with the other communication circuits. The longer circuits are equipped with loading coils.

Tabulation of Business Handled

| | |
|---|---|
| Messages and reports handled through terminal and relay offices for railroad operation, exclusive of commercial and local division business | |
| Morse per month | 400,000 |
| Printer per month | 500,000 |
| Telephone message per month | 108,000 |
| Calls handled through General Office manual exchange Philadelphia per month | 480,600 |
| Calls through New York semi-mechanical exchange | |
| Manually per month | 228,000 |
| Automatic per month | 324,000 |
| Information calls regarding train service through New York during busy pre-holiday period per day | 5,000 |
| Per busy hour | 700 |
| Pullman reservations handled New York busy day | 9,400 |
| Including by telephone with public | 2,600 |
| Telegraph message | 450 |
| Ticket sellers New York | 6,350 |

## PLANT FACILITIES

The following is a brief description of the plant facilities required to provide this service.

*Pole and Conduit Lines.* The presence of pole lines with crossarms and wires which, to many people, are unsightly things, has long been associated with railroads, but the Pennsylvania in recent years has placed all its wires in underground cables from New York to Philadelphia, 90 miles, and in a number of urban and suburban districts where available space, appearance, and continuity of service have been important factors. The six- and nine-duct conduit system from Wilmington to Washington, 108 miles, was recently completed, which makes practically an all conduit system from New York to Washington, 226 miles.

The wires and cables required for signal operation usually take the same general type of line construction as the communication system.

The main trunk line telephone system and the associated private branch telephone exchanges are shown in Fig. 2, which also shows both physical and phantom circuits and the number of each type in each group.

One important feature in connection with the operation of the telephone trunk circuits is the avoidance of frequent test points between division headquarters. Such intermediate points require cable and protection on each side, also test termination in the offices all of which are undesirable from standpoint of transmission and interruption to service.

The size of the conduit system in different sections and for different classes of service varies from single duct to banks of 78 ducts as in the Philadelphia area.

The pole line and cable system essentially form the back bone of the communication system, and, on account of its location along the railroad right-of-way, is exposed to many operating conditions to which the commercial lines are not subjected, as alternate routes cannot be chosen by the railroad to obtain more favorable conditions. These include routes closely paralleling many streams where glaze storms and fog are prevalent, close to oil refineries causing deterioration of open wire conductors and line hardware and coating of line insulators with resultant line leakage, cement plants which also cause excessive coating of insulators and line leakage, smoke and gases from coke ovens and industrial plants, and not the least of the troubles is the soot deposit on the insulators, telephone equipment and terminals due to the smoke from the engines along a busy section of railroad.

*Superposed Circuits.* Practically all the physical telephone trunk circuits shown in Fig. 2 together with many of the message and dispatching circuits are phantomed and simplexed or composited. These superposed telegraph and printer circuits generally are used for through or inter divisional service. The phantom circuits obtained from the trunks, dispatching and message circuits are used principally between the exchanges for trunk service.

*Loading Coils.* To provide satisfactory transmission for the trunk and tie lines between exchanges and for dispatching, power director and message circuits operating through the cable system, loading coils are installed at intervals of 6,000 feet. The insulation of the loading coil cable stubs and the windings of the coils is equivalent to that of the main cable to which they are connected, which is important, especially in electrified territory.

*Telephone Repeaters.* In order to provide satisfactory talking circuits between the principal exchanges shown in Fig. 2 it is necessary to install telephone repeaters at certain locations. These are of the "cord circuit" and "through line" types depending upon service involved. Arrangements have been made for the installation of "terminal" repeaters at Philadelphia which will improve service to and through that point.

*Armored Cable.* Paper-insulated, lead-encased cable protected with a double armor of galvanized tape is a more recent type of construction used along certain sections of a-c electrification. This protection is intended to eliminate or at least reduce very appreciably the trouble due to bullets in aerial cable construction, and also to reduce the induced potentials in the communication circuits due to the a-c electrification. When this type of cable is installed in underground construction the armor will be protected with wrappings of impregnated jute to prevent or retard corrosion.

*Portable Telephones.* Portable telephones are carried on work and wreck trains and are also used by telephone and signal maintainers and maintenance of way gangs. Where open wire line construction is used, the fish pole type of connection is made to the block circuit or to the train dispatcher's circuit depending upon the nature of the business. Where cable construction exists, the connections are made at the shelter boxes as above mentioned, the circuit being extended from the shelter box to the location where the telephone is to be used by means of insulated wire laid on the ground. Special arrangements are necessary to use these on simplexed circuits to avoid grounding the circuit when the set is placed on the ground.

*Radio.* Interest in radio for railroad operation has been manifested by the company for more than twenty years, and a number of experimental installations have been made, including land stations, on passenger trains, freight trains and on tug boats. At present there are no radio installations on the system.

*Testing Facilities.* To maintain the plant in good operating condition, proper wire chief's testing facilities and personnel are provided at the different regional and division headquarters and the general office, also such portable testing equipment as necessary including: meggers, bridges, telephone transmission testing sets and so forth. Routine testing for condition of plant permits location of defects in many cases before actual trouble develops.

*Acoustical Treatment of Offices.* In some instances the dispatcher's or message offices are located adjacent to the tracks or facing busy streets where traffic is heavy, resulting in excessive and objectionable noises in the operating rooms. In other cases the room noises, on account of the number of individuals or character of their work, are excessive. These conditions in several cases have been appreciably improved by the acoustical treatment of the ceilings, resulting in more satisfactory working conditions and a better grade of work.

TABULATION OF PLANT FACILITIES IN SERVICE

| | | |
|---|---|---|
| Pole line with wires and cables | 10,339 | miles |
| Open wire | 106,644 | “ |
| Underground cable, exclusive of laterals | 670 | “ |
| Aerial cable, exclusive of laterals | 230 | “ |
| Main underground conduit, principally 6- and 9-duct | 379 | “ |
| Cable conductors in service, exclusive of laterals | 58,000 | “ |
| Superposed phantom telephone circuits | 10,000 | “ |
| Superposed telegraph and printer circuits | 32,000 | “ |
| Telephone repeaters "through line" | 10 | “ |
| Telephone repeaters "cord circuit" | 8 | “ |
| Offices for handling railroad messages and reports and commercial telegraph business | 1,337 | “ |

## CONCLUSIONS

It is obvious that there are many and varied problems which develop in connection with the communication system which extends through the section of country where the greatest industrial and power development has taken place and where traffic is probably heaviest. The electrification project in itself between New York and Washington, with the many communication problems, is no small assignment, but the time and space allotted will not permit of a discussion of those features.

The underground system of conduits and cables extending through and between the different cities and towns is subject to many conditions requiring special consideration from standpoint of construction, maintenance and operation.

The increasing use of the telephone for long distance business between widely separated points on the system, with alternate routes where available, and the increasing use of printers, requires a high grade of plant and its maintenance for satisfactory service.

From the foregoing it may be seen that an attempt is being made to provide a communication system that will keep pace with modern developments in the art and which is considered a necessary adjunct to modern railroad operation.

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## Discussion

### COMMUNICATION REQUIREMENTS OF RAILROADS

(Niesse and Thayer)

### COMMUNICATION SYSTEM ON THE PENNSYLVANIA RAILROAD

(Forshee)

**W. H. Arkenburgh:** Certain information is given in this discussion which was not available to the authors of the paper at the time that they prepared it.

The General Electric Company has recently developed a system of communication for freight trains. This can be used to communicate either from front to rear end or from a train to a wayside point or from train to train. Fig. 1 illustrates the principal features of this system. The rails of the track are connected through impedances to any convenient ungrounded conductor parallel with the track. These impedance couplings are spaced approximately 1,000 feet apart. This distance will vary with local conditions. As shown in the figure the impedance consists of two condensers in series so arranged as not to shunt the signal track circuit. Where track circuits are not used this precaution is not necessary and other forms of impedance might be used. Upon the value of the impedance in effective ohms, depends the attenuation of the system which in turn determines the distance over which it will operate.

The equivalent of extremely simple carrier current receiving and transmitting sets are mounted on the locomotive and on the caboose of each train. These sets are connected in each case to inductor coils which are mounted just above the rails at minimum allowable clearance. These coils are so connected that instantaneous induced current values will be in the same direction in each rail. Automatic volume control is included to compensate for variation in distance between inductor coils and rails due to action of springs on rolling stock.

Electrical oscillations set up in the inductor coils by a transmitter will cause corresponding oscillations in the rails and thus in the system comprising the rails, the impedance couplings and the paralleling conductor. These oscillations are thus propagated over a predetermined distance and can be picked up from the rails at any point within that distance by any other set of inductor coils. In this manner two-way communication may be had between the front and rear of a freight train or between two trains if within the proper distance. Communication may also be had between trains on adjacent tracks or the system may be so arranged that there will be no cross talk. If receiving and transmitting apparatus is connected into the paralleling conductor at any wayside point communication may be had between such point and any train within a predetermined distance.

Provision is made for the protection of automatic block signal and other circuits. There will be no interference with the operation of automatic block signals or adjacent telegraph and telephone lines. If desired, any adjacent line wire may be used for coupling to the track. Thus advantage may be taken of wires normally used for the control of automatic block signals, for telephone or telegraph and also for power transmission.

Inasmuch as this system does not in any way depend upon space radio propagation it can be installed and operated without a license from the Federal Radio Commission.

**W. A. Jackson:** Mr. Forshee's paper gives me an opportunity to refute the statement that is so often made that the railroads are not progressive. So far as communication service is concerned, they have taken advantage of practically everything that is available. While Mr. Forshee's paper covers only the Pennsylvania System, with a few more or less minor modifications, it might be just as well applied to the railroad with which the writer is connected—the New York Central. The same remarks probably would be applicable to most of the other large railroad systems as well.

**H. W. Drake:** Two points may properly be emphasized at this time.

The first of these has been touched upon by Mr. Jackson and relates to the reproach so often leveled at the railroad managements to the effect that many of their present difficulties are due to failure to take advantage of improvements which might be obtained through scientific research and engineering development. I feel sure that any unbiased person reading these papers and the ensuing discussion will agree that there is little or no foundation for such a reproach in connection with the communication systems of the railroads.

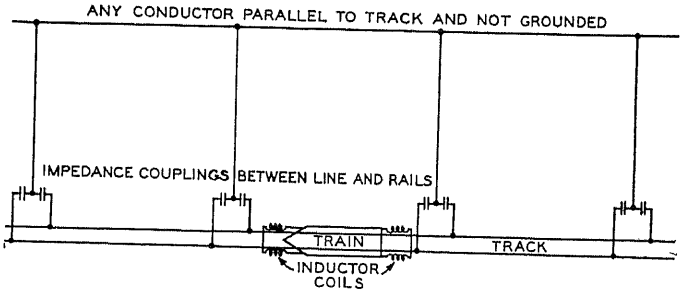
ANY CONDUCTOR PARALLEL TO TRACK AND NOT GROUNDED
IMPEDANCE COUPLINGS BETWEEN LINE AND RAILS
TRAIN
TRACK
INDUCTOR COILS

Fig. 1—General Electric Train Communication System

In the second place, the importance of the telegraph in railroad communication systems should be emphasized. We all recognize the advantages of the telephone in meeting many requirements of railroad service and this sometimes leads to a tendency to ignore the situations to which telegraphy is better adapted.

In support of this, attention may be called to the fact cited in the Niesse-Thayer paper that in a large railroad system, the number of telegraph messages may average from twelve millions to thirty-six millions per year. Further evidence appears in the table in Mr. Forshee's paper indicating that in addition to the very widespread use of the telephone on the Pennsylvania System, about eleven million telegraph messages per year are handled on railroad circuits. It is the writer's recollection that the latest report of the Interstate Commerce Commission shows that about 40 per cent of the railroad mileage of this country is still operated by telegraph. To these facts may be added mention of the suggestions made at various times in the past that careful engineering studies of the possibilities of telegraphy would often bring forth an economic solution of numerous problems which arise in railroad communication work.

Some mention has been made of the facilities made available to the railroads by the telephone companies. Without detracting in any way from the splendid work that has been done along these lines, it may not be out of order to emphasize also the similar provisions made by the telegraph companies in furthering the efforts of our railroad friends to provide satisfactory communication systems.

**I. C. Forshee:** The limitations of time and space did not permit of detail descriptions of any of the various services or facilities mentioned in the paper.

Since the plan in Fig. 2 was drawn, the underground conduit and cable between Wilmington and Washington have been completed and placed in service. This included telephone repeaters at Baltimore and provided an increased number of telephone trunks through the district.

The Wilmington-Washington cable is under constant gas pressure, divided into sections and equipped with alarm gages and alarm circuits which operate when the pressure drops in any section due to cable sheath faults. The cable on the New York Division is being similarly equipped.

Tie and trunk line dialing are being used to speed up the service in a number of exchanges where full automatic or semi-mechanical equipment are in service.

Since the paper was written metallic telegraph and printer circuits have been placed in service between New York and Philadelphia, with metallic repeaters at Philadelphia for direct operation with grounded circuits which extend to other points on the system, as from New York to Washington, Pittsburgh and Chicago.

The railroads recognize the assistance given them by the commercial telephone and telegraph companies in plant development, maintenance and operation to which Mr. Drake referred and for which the railroads are duly grateful. There are many conditions which are peculiar to the railroad communication plant, however, for which the railroad engineers must develop their own solutions.

The telegraph, as Mr. Drake mentioned, is still used extensively for handling messages and reports between divisional and regional headquarters and between the general office and those points, and probably will continue to be so handled for some time to come, but the local message and report business on the divisions is very largely handled by the telephone and printer.

The a-c electrification has developed many interesting problems in the railroad communication plant, but a description of them is hardly feasible in this paper and discussion. It may be said, however, that the communication system is operating satisfactorily.

Train announcing systems which were popular a few years ago are now conspicuous by their absence, and in many of the larger stations one never hears a train announced either on its departure or its arrival.

# Railroad Signaling and Train Control

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SOON after the first public railways were built in England early in the nineteenth century, their managers discovered the need of some method of conveying information and instructions to train crews. The first signals used were crude affairs of many shapes and colors and confusion naturally resulted because of different meanings having been assigned to them on the different roads. The first real improvement was made in the year 1841 when C. H. Gregory adapted the semaphore to railway uses.

Tradition says that the semaphore, which consists merely in the attachment of a movable arm or blade near the top of a pole, was invented by a talented Greek named Polybius, several hundred years before Christ. But the idea doubtless came from the original source of a man making signs by moving his arms. The Romans, and afterward the French, Germans, Russians and English, employed it for both civil and military purposes before the invention of the electric telegraph.

As applied to railroads, the semaphore consists of a blade, three to four feet long, attached to a spectacle in which are mounted colored glasses behind which a lamp is placed for night indications. When the arm is in the horizontal position, with red light, "stop" is indicated. When the arm is 45 degrees above the horizontal, with yellow light, "caution" is indicated. When the arm is 60 degrees below the horizontal or 90 degrees above the horizontal, with green light, "proceed" is indicated.

### THE TELEGRAPHIC BLOCK

Charles Minot, superintendent of the Erie Railroad, made the first practical application of the Morse telegraph for the sending of train orders, in 1851. With the first train order came telegraphic train dispatching which offered an effective means for reducing the delays incident to operation under timetables. Two forms of train orders are in use, form "31" and form "19." Form 31 is receipted for in writing by the conductor of the train addressed. Form 19 is receipted for by the station operator, who is responsible for the delivery of the order to the conductor and engineman of the train addressed. Because of this difference in delivery, a moving train is required to stop for a 31 order but need only slacken speed for a 19 order.

Two train order signals are provided at each station, one to govern the movement of trains in each direction for single or double track. These are usually placed on one mast and the semaphores are generally manually operated by levers in the station. They are held normally "clear" and are placed in the "caution" or "stop" position when an order is to be delivered to an approaching train. If a three-position indication is employed, the 45-degree position usually signifies that a 19 order is to be received and the horizontal position indicates a 31 order. In two-position signaling, the horizontal position means either a 19 or 31 order.

### MANUAL BLOCK SIGNALING

With the space interval method, train movements are directed as in the time interval method, by timetables and train orders, and in addition, by block signals. Space is maintained between trains by dividing the track into sections with fixed signals to govern the movement from section to section. Blocks may vary in length according to traffic requirements.

In the manual block system trains are spaced by the display of manually operated signals based on information conveyed by telegraph, telephone or bell code between two stations. Signals govern the use of blocks only and do not supersede the superiority of trains or dispense with the use or observance of other signals, unless otherwise provided. Several systems of operation are in use; absolute block for all movements on the same track; absolute for opposing, and permissive for following movements on the same track; absolute block or permissive block for following movements on double track.

The block signals are held normally in the "stop" position and are cleared only on the approach of a train when the block ahead is clear and are restored to the normal position after the train has passed. A "proceed" indication allows a train to proceed only if it has authority by timetable or otherwise and gives exclusive right to the track to the next block signal. Each block operator is ordinarily required to keep a record of passing trains. The simple manual block system is operated by rigid rules but without electrical or mechanical check on the block operators.

### CONTROLLED MANUAL BLOCK SYSTEMS

Several types of controlled manual block signaling are in use, all of which are operated on the principle that the cooperation of two persons, one located at either end of a block, is necessary before any signal can be cleared to admit a train into the block. Although this system is operated manually, electrical and mechanical means are used to provide more or less complete control. The more highly developed systems employ either short sections of track circuits at stations or complete track circuit control which provides protection against open switches, broken rails, or cars inside of clearance points and gives the block operator a continuous indication of the condition of the block.

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Approach and advance block signals are often used in controlled manual block signaling. The installation of an advance block signal permits trains to use the switches between it and the block signal and expedites the movement of trains from block to block when traffic is heavy. Power-operated approach signals may be provided which indicate caution at all times, except when the block signals are clear, switches set for main track, and the section between the approach and block signals is unoccupied. Outlying switches between block stations may be electrically locked and controlled by the operator in the block station to the rear.

In controlled manual block operation, the block signals govern the use of the blocks and their indications supersede timetable superiority and take the place of train orders, unless other provisions are made. These signals do not, however, dispense with the use or observance of other signals which may be required.

### AUTOMATIC BLOCK SIGNAL SYSTEMS

Automatic block signaling is controlled entirely by the condition of the track and eliminates the human agency. The fundamental requirement of any automatic signal system is that a failure of any sort on account of interruption of power, broken rail, broken wire, or other defects of apparatus, will result in the signals immediately displaying their most restrictive indications. The design of all modern signal equipment is based upon this fundamental requirement.

The Standard Code of the American Railway Association, Block signal and Interlocking Rules, adopted January 17, 1928, shows the recommended signal indications, names and aspects, to which are added the rules governing typical color and position combinations. The roads usually follow the A.R.A. recommended practises as far as possible, but in some cases it is considered necessary to amplify the indications to suit special requirements on the various lines.

The conditions which determine the length of the block sections and consequently the number of trains that can be run in a given time are: (a) the maximum speed; (b) the braking power and consequent distance required in which to stop a train running at maximum speed; (c) the grade and alinement of the track; (d) the time required for the signals to change indications; (e) the length of the trains and (f) the location of stations, interlocking plants, passing tracks, and other local conditions which cause irregular spacing of the signals.

To provide for maximum train service, it must be possible to run trains at the greatest speed local conditions will permit, the blocks being of such length as to allow this speed to be attained with safety. The engineman must be informed at all times as to track conditions ahead and if it should not be safe to proceed, he must be warned at a point a sufficient distance back of the stopping point so that the train may be brought to a stop before passing the signal. On multiple tracks signaled for traffic normally in one direction only, a stop and an approach signal indication are generally provided back of a train.

Single track signaling may consist of the overlap scheme or the absolute-permissive-block scheme. In the overlap scheme, if two trains moving in opposing directions should pass clear signals at the same instant, other opposing signals are so situated that each train will encounter a stop signal before entering an occupied block. This is accomplished by carrying the control circuits for one home signal full braking distance beyond the next signal in advance, which governs in the same direction, and making the continuity of the circuit depend upon the condition of the track section or sections ahead of the last named signal. Signals for trains moving in the opposing direction have their control circuits overlapping the next home signal in advance in a similar manner.

The absolute-permissive-block scheme of single track signaling provides head-on protection from one passing track to another passing track while permitting following movements to be made.

The leaving signal at the end of a passing track is made a positive "stop" signal while the entering signals to passing tracks and station limits are automatic permissive signals, the most restrictive indication of which is "stop; then proceed." In operation, this system is arranged so that when a train passes a positive signal at the leaving end of a passing track, the opposing positive signal is set at stop and all opposing intermediate signals assume their most restrictive indication, thus holding any opposing train at the other end of the block. The opposing signals clear after the train passes them and at the same time the train is protected from a following movement by a stop and an approach signal back of it.

### AUTOMATIC TRAIN CONTROL SYSTEMS

Every successful scheme of automatically applying the brakes to stop or control the speed of a train is based upon the fact that opening of the air brake pipe line results in application of the brakes. Two orders of the Interstate Commerce Commission, issued June 13, 1922 and January 14, 1924, respectively, and subsequently modified so that an engineman, if alert, may forestall the brake application and proceed without stopping, required certain railroads to select and install the type which each considered most suitable for its particular conditions, in accordance with specifications and requirements prescribed by the Commission.

Every type of train control device requires a roadside element designed to coact with an engine-carried element so as to transmit to the locomotive the conditions existing on the track as would be indicated by a modern automatic signal system. After the information is conveyed to the engineman, it may be used either to apply the brakes or to indicate by means of a cab signal, visible or audible, the conditions which exist. The devices may be classified in two general groups, the intermittent and the continuous. The intermittent may be further subdivided into the contact type and the non-contact type. The contact type depends for its operation on a physical contact between the train element and the roadside element while the non-contact type depends on an electrical or magnetic impulse without physical contact between the train element and the roadside element.

The trend has been decidedly toward the induction type of equipment and no installations of the contact type have been made on any road except the three which had such installations at the time the orders were issued. One of these subsequently changed to the induction type.

The intermittent type of device receives its control at certain fixed points along the roadside, usually at or near a signal, and is incapable of reflecting any change in track conditions between any two of the indicating points. It is an adjunct to the automatic block signal system for the purpose of preventing that class of accidents which are due to the failure of employees to observe, understand or obey signal indications. Most of the intermittent induction types in service employ an inert roadside element consisting of a laminated core upon which are mounted coils, the terminals of which are connected through a relay of the signal system. No energy is required for the track element.

The locomotive receiver carries two coils mounted on a laminated core, both of which are energized by direct current from the headlight generator. Associated with these are a number of circuits and relays on the locomotive which provide a means for producing a brake application. In all the variations of this type, the brake application is initiated by a sudden reduction of current flow in the main locomotive relay which is produced by the action of the receiver passing over the track inductor when the circuit of that inductor is open through the roadside relay in the stop position.

The basis of the continuous train control systems which have been developed, is the inductive fields produced by alternating current flowing in the rails. Collecting coils are mounted on the locomotive so as to move in the field produced around the rail. The current which is induced in these coils is transmitted to amplifying apparatus on the locomotive. The amplified current in turn controls the circuits that operate electro-pneumatic valves directly controlling the brake-pipe pressure. Circuits are also provided for a visible cab signal which constantly shows the conditions of the track. Any change in conditions in a clear block, which calls for a reduction in speed, is immediately reflected by a corresponding indication in the cab. The brakes are also applied unless properly forestalled by the engineman. Conversely, a more favorable condition in a block is immediately transmitted to the engineman and the train does not have to move under restricted speed until the next signal is reached.

The continuous type of device functions on a closed circuit, which is the basic principle of signaling, failure of any part causing a stop application. It may be used with or without permissive signals on the roadside and four railroads are demonstrating the practicability of operating without roadside permissive signals. The addition of a centrifugal governor, usually applied to the forward pony truck axle of the locomotive, provides for the automatic control of the train at the varying speeds required by different track conditions.

Alternating current of 100-cycle frequency is favored for use in the rail circuits to avoid possible interference from commercial power sources. To provide four cab indications and maximum protection against inductive interference from other circuits, a specially designed code transmitter may be used in connection with the roadside apparatus, consisting of a constant speed induction motor geared to a shaft carrying "coding" cams which operate contacts to interrupt the 100-cycle alternating current. Code frequencies of 80, 120 or 180 interruptions per minute for the approach, approach restricting, or clear indications, respectively, are impressed upon the track, depending upon the condition of the track in advance. The engine equipment is designed so as to respond only to the track current frequency when it is interrupted at the proper rate. Absence of current in the rails gives the stop indication.

Operating officers and enginemen report the safety features in cab signaling, which make it independent of fogs, storms or other obstructions to vision, as one of the greatest advantages of train control.

The first orders of the Commission having accomplished their purpose of promoting extensive development of automatic train control, an order was issued on November 27, 1928 to the effect that the railroads would not be required by order to install any more train control at present but that they are "in no way relieved from the responsibility which rests upon them to provide additional protection when needed in territory now protected by automatic signals." This leaves the roads free to use train control, cab signals, or such other means as they may see fit, to secure additional protection, particularly on dense traffic lines.

## HIGHWAY GRADE CROSSING PROTECTION

The protection of highway grade crossings is an important part of railway signaling work. Watchmen, with or without manually operated gates, are often employed at busy points in cities. An audible warning, controlled by track circuits, is objectionable in residential districts and usually does not provide adequate protection for closed automobiles in the open country. Therefore, the majority of crossing protection installations consist of visual rather than audible signals.

The requisites for automatic signals for highway crossing protection, as set forth by the American Railway Association and the American Railway Engineering Association, specify that the signal "shall present toward the highway, when indicating the approach of a train, the appearance of a horizontal swinging red light and/or disk" A Committee on Grade Crossing Protection appointed by the American Railway Association in 1930 has published its recommendations in its Bulletin No. 1. These recommendations agree with those of the National Conference on Street and Highway Safety. They are endorsed for future installations and renewal of existing devices.

### INTERLOCKING SYSTEMS

In recent years there have been many refinements in all types of interlocking. Electric detector circuits have generally replaced detector bars. Approach locking, route locking, sectional route locking, check locking, time locking and time releasing have come into general use. In addition to the mechanical locking in the machine, routes are controlled, interlocking levers are locked and switches are locked electrically by the presence of a train upon a given track circuit controlling a track relay which in turn interrupts the circuits of such locks, making them effective. As soon as a train reaches the approach circuit the route lined up is locked automatically and can be taken away only by the use of a time release which requires an elapse of one or two minutes after the home signal has been set against the train. If the train should pass the home signal the route is then locked the full distance ahead through the sectional route locking but the switches are released behind the train as each section is passed.

Where two interlocking plants are situated close together as in terminals and at tunnel, bridge or yard locations, and each has signals governing in the direction of the other on the same track, it is necessary to provide traffic locking to prevent any two such opposing signals being cleared at the same time. In electric and electro-pneumatic plants a separate lever is usually provided in the machine in each tower for each track over which reverse movements are to be made. These levers are connected with the mechanical locking in such a way as to control the direction of traffic. Bridge locking is employed in connection with movable bridges to prevent signals governing the approach to the bridge being cleared unless the bridge is locked in its closed position.

The signals used at an interlocking plant may be of either the semaphore or light type. The recommended indications, names and aspects are shown in the Standard Code of the American Railway Association, Block Signal and Interlocking Rules.

The selection of a power or a mechanical plant depends upon local conditions, among which are the distances from the tower to the switches which are to be operated and the frequency of operation. A small mechanical plant is simple to install and maintain, has few failures and is low in first cost. A power interlocking on the other hand, permits operation of switches and signals a longer distance from the tower, requires a smaller building for housing the machine, provides quicker operation, and in many cases, entails less operating labor.

Power interlocking plants are generally used at drawbridges, stations, and terminals where a mechanical plant cannot be operated to the best advantage. At large terminals, it is necessary to provide, in addition to the usual safety features, electrical indications to inform the operators of just what is transpiring at all times because they are frequently not in a position to see the tracks. The location of trains is indicated on a track diagram on which small spotlights mark the occupied sections of track, both within the plant limits and approaching the plant. Lever lights are provided on the machine to indicate when a signal is clear and whether or not a switch lever can be reversed or restored.

At passenger terminals some form of train starting system is installed to provide means of inter-communication between gateman, conductor, and towerman. Push buttons and light indicators, with or without buzzers are generally used.

There is a trend toward greater use of automatically controlled signals for governing train movements at crossings, junctions and gauntlets. Protection of this nature is termed "automatic interlocking" and the principle of operation is similar to that of automatic block signaling. The home signals normally indicate "stop" and, if conditions permit, the signal clears when an approaching train enters the approach track circuit. When the signal clears, all conflicting signals are held at "stop." Provisions are made for releasing the signal after the elapse of a time interval in case the train is delayed for switching or other purposes while occupying the approach or clearing section, so that movements can be made on the other line without flagging over the crossing. Approach signals are usually provided and a speed restriction of 10 to 25 miles per hour approaching the plant, is required.

Automatic interlockings are proving of great operating advantage and are the simplest and most economical type of signal protection which can be provided for a railroad grade crossing and other simple layouts.

### FREIGHT CLASSIFICATION YARDS

At large freight terminals a hump is provided in the yard lead track with an incline so arranged that the cars move by gravity into the various classification tracks. In past years, the majority of these gravity yards have been operated manually, men being required to throw the various yard switches and ride the cars in order to apply the brakes. The disadvantages of manual operation are that a large number of men are needed, both cars and lading may be damaged, car riders may be injured, weather conditions seriously affect the capacity of the yard, and the cost of operation is high. Power-operated switch machines are now being used which are controlled from a tower. As the cars move over the hump, the operator knows from his switch list upon which track each cut of cars should be placed and he operates the switches accordingly.

Power-operated car retarders are also controlled from the tower. A set of brake shoes is placed along each side of and parallel with the rail and arranged to move towards the rail to clamp the sides of passing car wheels to retard the motion of the car. The control lever is arranged to give three degrees of retardation, as well as to open the retarder for the movement of the car. In order to prevent damage in case cars get through the retarders without sufficient retardation, power-operated skate placing machines are installed where necessary to place a skate on the rail ahead of a car to arrest its movement.

The control and operation of the switches, retarders and skate machines may be entirely electric or electro-pneumatic, all control levers being in the same machine located in an elevated tower so that the operator of each group can see the yard and observe the location of the cars as they pass through the switches and retarders. Suitable flood lighting is provided for night operation. The several operators are directed by a yard master by means of a loudspeaker in each tower. Pneumatic tube and teletype systems are used in sending switch lists to and from the yard offices.

While in some respects the signal appliances employed at hump yards are similar to those used at interlocking plants, there are several points of difference. There is no interlocking of the levers and the signals are few in number and have special indications. The signals may be of either the semaphore or light type. One signal is usually provided for each direction at the top of the hump with repeater signals in the yard as required. For movements over the hump the usual indications are "stop," "hump slow," "hump fast" and "back-up." The indications of the signal governing movements in the opposite direction, known as the "trimmer signal," are "stop" and "proceed."

Car retarder installations are improving service to shippers and reducing operating expenses by reducing motive power expense, increasing car capacity, reducing delays and personal injuries, reducing damage to equipment and lading, and consolidating classification yards.

## REMOTE CONTROL OF OUTLYING SWITCHES AND SIGNALS

The need for reducing the delay time of trains on the road has resulted in the development of a low-voltage electric switch and lock machine for application to outlying switches at ends of double track, passing tracks, junctions and entrances to yards where they may be remotely controlled by an operator or other attendant at a station or interlocking tower a mile or more away. The switch points are prevented from being moved while engines or cars are on or adjacent to the switch through the medium of electric track circuit control. Signals control train movements over the switch and provide additional safety in that a train taking siding must pass the fouling point before another train can get an indication to proceed on the main track. If near an interlocking plant the apparatus required for outlying switch control may be operated by levers in the interlocking machine. Where installations are made adjacent to manual block or station offices, a small table machine, equipped with locking devices and indicators is used for the lever control of the switch and signal units. The usual approach, detector and route locking used in interlocking practise can be provided. Such an arrangement allows trains to enter or leave sidings or yards, or to turn out at junctions, without stopping or reducing speed below that safe for passing through the turnouts.

## TRAIN OPERATION BY SIGNAL INDICATIONS

Although block signals were first installed as a safety measure to supplement the train order system owing to the weak link of human fallibility, the remarkable advance in the art of signaling and demonstration of the reliability of signal indications soon relegated the train order to a distinctly inferior position. The development of directional traffic control between interlocking plants and the signaling of intermediate tracks for operation in either direction, together with the remote control of outlying switches, brought about the operation of trains by signal indication only, on both single and multiple tracks. This was first done locally between interlocking or block stations and permitted the utilizing of both track and equipment to their full capacities by shortening headways between trains and operating superior trains around inferior trains without stopping, thus avoiding clearance time for inferior trains and long waits at passing points when the overtaking train was delayed. This arrangement was extended to include several adjacent sections, all operated under the direction of the dispatcher without the use of written train orders or train rights by timetable or direction. It resulted in the handling of increased traffic at higher speeds and postponed the construction of additional tracks.

## CENTRALIZED TRAFFIC CONTROL

To reduce the cost of operation and secure a more flexible layout a system of control circuits known as "centralized traffic control" has been designed which reduces the number of line wires to a minimum and places the control of all switches and signals of an entire district or division directly in the dispatcher's office. The direct wire systems, which are considered more economical for distances of only a few miles, require two or three wires for switch and signal control and additional wires for the approach indications which are essential if unnecessary stopping of trains is to be avoided. For long distances, and especially when a number of groups of switches and signals is to be controlled, a code-relay system is used which requires but two wires, irrespective of distance. By the transmission of interrupted currents which form codes similar in character to Morse telegraph signals consisting of dots, dashes, and spaces, a selection of the proper relays is effected to control the operation of switches and signals at any desired location and to transmit back over the same two wires light indications showing the operation of corresponding switches and signals and whether the track circuits are occupied or unoccupied.

The control equipment consists of a machine containing levers for operating the switches and signals and having a track model suitably equipped with colored lights to aid the operator in visualizing all train movements under his control. An automatic train graph records the movement of each train on a graphic train sheet. These indications are made possible through the medium of the track circuits.

The switches at points along the right-of-way are operated by electric switch machines, similar to those used at interlocking plants, except they have a dual-control so that they may be operated electrically by the dispatcher for regular moves or mechanically by the train crew for switching moves or in case of emergency. The dispatcher's consent must be secured, however, to operate any of these switches by hand. Telephones are provided for use of trainmen in communicating with the dispatcher.

The switch machines and the signals at the end of a passing track, at a junction or a crossover, form a controlled group which is essentially a small interlocking plant. A signal cannot be cleared until the approach track circuit is occupied and the switches are properly set. Adjacent groups are electrically interlocked with each other to prevent conflicting signals being cleared either by the automatic operation of the signals or by any manipulation of control levers that the dispatcher may make. Approach locking is provided to prevent the possibility of a switch being operated after an approaching train has accepted a proceed signal governing over the switch, and detector locking prevents the operation of the switch while a train is passing over it.

One of the outstanding features of the dispatcher-controlled system is that instructions are not relayed or dependent upon memory for their delivery. Neither are they subject to deficiencies in memory of the persons executing the orders. Instead, trains receive their orders by signal indication, displayed at the point where action is required. Furthermore, meets between trains on a single track are greatly facilitated, a large percentage of them being non-stop meets.

### TREND IN ART OF RAILWAY SIGNALING

Specifications for the complete installation of the various signal and interlocking systems and requisites covering the control circuits are published in the Manual of Recommended Practise of the Signal Section of the American Railway Association. The rules governing the operation of signals and trains under these systems are contained in the Standard Code of the American Railway Association.

The railroads are profiting, not only in reduced first cost but also through better performance, by the use of the modern standardized devices and control systems which have been developed through the work of the Signal Section and its predecessor, the Railway Signal Association, with the cooperation of the manufacturers of signal appliances.

Efficient transportation is largely dependent upon an efficient direction of train movements. The developments in the art of railway signaling, based upon the fundamental track circuit, have proved that directing train movements by signal indications is both practical and efficient. Abundant experience in every case has shown substantial economic advantages, an increase in safety, a reduction in train delays, an increase in ton miles per train hour and a decrease in total ton-mile cost.

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## Discussion

For discussion of this paper see page 313.

# Modern Signaling on the Reading Railroad

BY E. W. REICH* and G. I. WRIGHT†
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*Synopsis.—A description of one railroad's signal system limits most of the detail to the type of signals and interlockings standard on that particular road, however, there are many features of interlocking and signal control that are common to most modern signal systems. These features are described briefly in the paper.*

*Following a brief description of the earliest forms of signaling employed on The Reading Railroad, this paper describes the Reading's most recent installation of 100 cycle alternating current color light signaling.*

*The 100 cycle frequency was first used in the continuous coded train control territory, where a distinctive frequency was required to eliminate any possibility of foreign inductive interference, and was later adopted for use in electrified territory, as the range between the 100-cycle signal frequency and the 25-cycle electrification frequency permitted the use of frequency selective track relays.*

*The main features of the Reading's loop and code systems of continuous automatic train control and those of the automatic signaling and power interlockings are described in this paper.*

THE Philadelphia and Reading Railroad (now Reading Company) was one of the pioneer roads in the installation of automatic signaling and interlockings. The first form of signaling used was a manually-operated three-sided revolving tower, mounted on top of a raised signal cabin. The sides or faces of the signal towers were rectangular in shape, approximately four feet high and three feet wide, and were painted red, yellow or green for the day indication, with colored lights for the night indication. These signal towers were used to protect train movement on curves and were located on the side of track from which the best possible approach view could be obtained. When a train passed the signal, the towerman would turn the tower so as to display the red or stop indication and after a period of five minutes would turn it to the caution indication, following another period of five minutes he would place the signal in the clear position. This form of protection was, of course, very unreliable, as the towerman had no means of determining how far a train had actually advanced beyond the tower.

The first interlocking installation by the Reading Railroad on record is of a mechanical machine that was installed at Wayne Junction in 1880. This was followed by other installations of a similar type at most of the important junction and switching points. Operating officers were quick to recognize the advantage of controlling the position of switches and signals from a central point and the policy adopted by the Philadelphia & Reading Road placed it in a position along with other progressive roads to further the development of improved types of interlockings. This is best illustrated by noting that the Wayne Junction plant has had four complete replacements of the interlocking machine since the original installation. A mechanical plant served from 1880 to 1901; at this time a low pressure air machine with pneumatic operated switches was installed. Air for the switches was directly controlled by valves in the machine, including an air-operated indication device on the machine which indicated following the complete movement of switch points. The low pressure air plant required a multiplicity of small pipes radiating from machine to operated units and never proved very practical.

Following the installation of the low pressure air machines, rapid strides were made in the development of more practical power-operated interlockings. In 1911 the existing machine was replaced with an all-electric interlocking machine which was in turn replaced in 1929 by an improved type of all-electric machine. The last change was made in connection with the Reading's suburban electrification program.

Automatic signals were first installed on a portion of the Reading's main line in 1895, the signals were of the Hall disk type, which type of signal was standard until 1902 when the first two arm (home and distant) semaphore signals were installed. Following the advent of semaphore signaling the road's standard was changed to a single arm three position upper quadrant semaphore with marker light. This type of signal was in use until 1924 when the Reading, following experimental tests with various types of light signals, adopted the color light signal as standard.

As the most recent signaling installation on the Reading is located within its suburban electrified area, we shall confine our description to this territory.

*Power Supply and Distribution.* The development of automatic train control and frequency selective track relays now commonly used in a-c electrified territories made necessary that signal frequencies be distinctive and free from the inductive effects of other a-c systems. To meet this condition a 100-cycle signal frequency is used, requiring converter sets at signal substations, where the supply frequency is converted to 100 cycles.

Electrical energy for the operation of automatic signals and interlockings is distributed at 4,400 volts from ten signal substations located approximately twenty miles apart. Signal power is normally supplied from five of the stations; the remaining stations are located at the opposite end of each normal feed power section, automatically controlled so as to take the signal load in the event of a failure of the normal supply.

Throughout all of the terminal territory the signal circuits are carried in a concrete encased fiber duct line

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*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

using two-conductor No. 2 or No. 4 lead-covered cable. In the outlying territory, signal lines are run in open wire on a wood pole line or on catenary structures.

Signal substations are located as follows:

| Location | Kva |
|---|---|
| Reading Terminal<br>60-cycle Reading Company supply | 120 |
| Wayne Junction<br>60-cycle Philadelphia Electric Company | 2–120 |
| Neshaminy Falls<br>60-cycle Philadelphia Electric Company | 120 |
| Yardley<br>60-cycle Philadelphia Electric Company | 30 |
| Chestnut Hill<br>25-cycle electrification circuit | 60 |
| 16th Street Junction<br>60-cycle Reading Company supply | 50 |
| Norristown<br>25-cycle electrification circuit | 75 |
| Nicetown<br>60-cycle Reading Company supply | 10–50 |
| Gladwyn<br>60-cycle Philadelphia Electric Company | 10–50 |
| Jenkintown<br>60-cycle Philadelphia Electric Company | 60 |
| Hatboro<br>60-cycle Philadelphia Electric Company | 50 |
| Lansdale<br>25-cycle electrification circuit | 75 |

All signal substations are non-attended except the Wayne Junction station where four signal lines radiating from this point are energized from a 100-cycle bus. The standby or reserve sets are started automatically and closed in on the line when machine voltage builds up to normal. Each station is controlled over a line relay which prevents it from closing on the line when the other station is feeding.

All frequency changer sets are provided with thermal protection on the motor and the generator has a full complement of under-voltage and over-voltage relays checking performance; outgoing 100-cycle feed is protected with a manual reset overload relay.

At Wayne Junction where there is parallel operation of two 120-kva frequency changer sets feeding a 100-cycle bus, the use of induction type motors necessitates special provision for synchronizing.

During part of the day it is possible to carry the load with one machine, but at peak load periods the second machine must be operated. At the time this second machine is closed in on the bus the first machine is operating at nearly full load, its frequency being synchronous less the slip frequency. To compensate for the difference between the frequency of the loaded and the incoming machines, an arrangement is used whereby a phantom load is placed on the incoming machine. This provides control of the incoming machine, regulating its speed to approximately that of the operating machine. The control circuits are arranged to drop the phantom load automatically when the second machine is connected to the bus. A current-compensating circuit operating on the machine voltage regulators insures an equal division of the wattless current. The division of power current is, of course, determined by the speed of the respective machines. The slip curves of the above machines coincide very closely and the power current of the two machines is equal under all load conditions.

The exacting voltage regulation required on signal lines makes it prohibitive to have an instantaneous drop in voltage when dropping one machine from the bus. To overcome this a circuit arrangement eliminates the current compensation and over-excites the machine that will remain on the bus. With this arrangement there is no noticeable drop in signal voltage in placing a machine on or off the bus.

Transformers are 4,400/110-volt, oil-cooled, of capacities varying from ¼ to 15 kva. No grounding is permitted of either the primary or secondary transmission systems, thereby isolating the signal circuit from the effects of other grounded systems. At transformer locations in open-wire territory both lines of 4,400-volt circuit are protected by lightning arresters. A separate earth connection is run to the transformer shell.

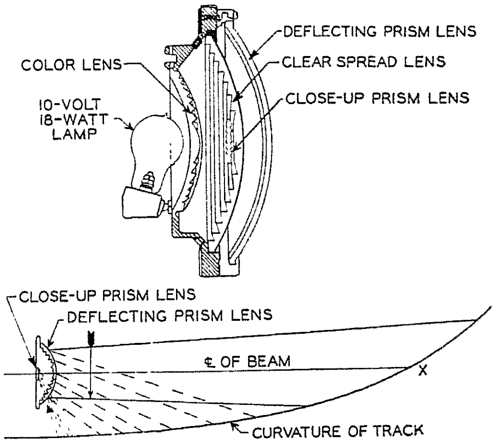


Fig. 1—Lens Arrangement and Method of Focusing of a Light Signal

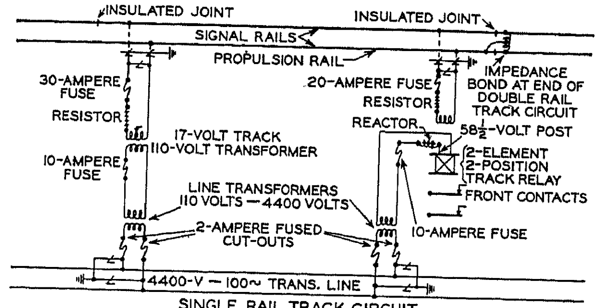
Solid lines represent beam spread of clear lens
Broken lines represent beam spread of deflecting lens
Dotted lines represent concentrated light beam for close-up view

Lighting for all the smaller stations in the electrified territory is taken off the 4,400-volt 100-cycle signal line. Where a station lighting and signal connection is required at the same location a double secondary transformer is used, thus permitting use of a grounded secondary lighting circuit without introducing grounds in the signal circuit.

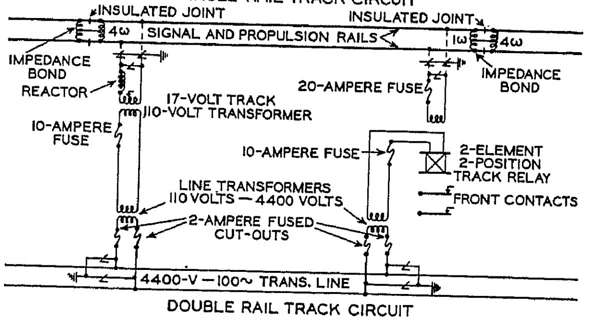
*Signals.* The modern signals are all of the long range color light type arranged with two or three light units; light signal cases are ventilated, and the entire lamp unit and case is assembled so that the lamp filament is in the exact focal point of the lens system. Accurate alignment is procured in the field by the use of a portable sighting telescope. On tangent track the signals are focused for a long range indication. On curves the signal is focused to the far point of the curve where the indication should first be picked up by the engineman. Continuous indication for approach on curves is provided by using a

10- or 20-deg deflecting prism or spread lens in which light rays are deflected in a horizontal plane toward the arc of the curve.

The lamp unit consists of a doublet lens with outer lens clear and inner lens colored. The lamp receptacle is supported in fixed relationship to the lenses. Thus, lamps are interchangeable. In addition to the doublet lens each unit has a small deflecting lens held in position by a spiral spring, immediately back of the center of the front or clear lens. This lens is commonly called a close-up prism and provides an intense color display in the center of the signal front lens, when the train is stopped immediately under or opposite a signal. Lamps used are of the double filament type rated at 10 volts, 18 watts. These are lighted at 9½ volts (slightly less than lamp rating) to insure a long burning life.



SINGLE RAIL TRACK CIRCUIT



DOUBLE RAIL TRACK CIRCUIT

FIG. 2—TYPICAL SINGLE AND DOUBLE RAIL TRACK CIRCUIT

Signals are located on masts to the right of, or on catenary structures immediately over the right rail of the track governed. Where signals are mounted on catenary structures they are located 21 ft above top of rail. Ground masts are located to the right of track governed, with near side of mast 10 ft from the center line of track. Signal units of interlocking signals are arranged as follows:

*Two-unit Signal.* Center of red lens of bottom or slow-speed unit 10 ft above top of the rail with 12 ft spacing to center of red lens in top unit.

*Three-unit Signal.* Center of red lens of bottom or slow-speed unit 10 ft above top of rail with 7 ft spacing to middle and 5 ft middle to top unit.

*Automatic Signal.* Center of red lens of marker light or third block indication unit 10 ft above top of rail and 7 ft between red lens of marker and automatic signal unit.

*Aspects and Indications.*

Interlocking Signals

| Rule | Aspect | Name |
|---|---|---|
| | | Interlocking Signals |
| 601A | Red-Red-Red<br>Red Red<br>(dwarf) Purple | Stop<br>(Route is not set) |
| 601B | Yellow-Red-Red<br>Yellow Red | Approach<br>(Prepare to stop at next signal. Train exceeding medium speed must at once reduce to that speed) |
| 601C | Green-Red-Red<br>Green Red | Clear<br>(Proceed at time-table speed) |
| 601D | Red-Yellow-Red | Medium Approach<br>(Proceed at not exceeding medium speed prepared to stop at next signal) |
| 601E | Yellow-Green-Red | Approach medium<br>(Approach next signal at not exceeding medium speed) |
| 601F | Red-Green-Red | Clear medium<br>(Proceed at not exceeding medium speed) |
| 601G | Red-Red-Yellow<br>Red Yellow<br>(dwarf) Yellow | Restricting<br>(Proceed at restricted speed) |
| | | Automatic Signals |
| 501AA | Red-Red | Stop and proceed<br>(Stop then proceed block is not clear) |
| 501B | Yellow-Red | Approach<br>(Prepare to stop at next signal. Train exceeding medium speed must at once reduce to that speed) |
| 501C | Green-Red | Clear<br>(Proceed) |
| 501E | Yellow-Green | Approach medium<br>(Approach next signal at not exceeding medium speed) |

*Automatic Signals.* In general the automatic signaling is of the three indication—two-block type, however, at approaches to interlockings where a restricted route signal may be displayed or where the spacing between automatics does not provide sufficient braking distance four indication—three-block signaling is installed.

Existing installations made prior to electrification had both polarized line or clearing and track relays. In electrified territory where track circuits are limited to the use of two-position frequency track relays, recent installations have been made with neutral line control. This form of control is adaptable for future extension of cab signal territory.

Line control circuits are normally energized, but the signals are lighted only during the time a train is in the approach block to the signal and until the block beyond the signal is cleared. Where more than one track is signaled in the same direction, signals for both tracks at the same location are lighted by the approach of a train on any one track.

Automatic signal control provides that a stop indication be displayed when

Train, engine or car is in the block immediately in advance of the signal.

Any switch or derail in block is reversed or switch points not fully closed in their normal position. A switch point tolerance of less than ¼ in. is permitted.

A rail is broken, interrupting track circuit.

Cars extend beyond the fouling point on sidings.

*Interlockings.* Electropneumatic interlocking plants are installed throughout most of the terminal territory where frequency and speed of operation is an important factor. However, power interlockings are not all of the electropneumatic type. There are a number of all-electric plants in service. Interlocking circuits provide a standard arrangement of approach, sectional, route and detector locking.

*Approach Locking.* This is an arrangement of electrical control which permits changing signal from the proceed to the stop indication, but acts to prevent any change of route in advance of an approaching train. A release is provided in the approach locking circuit through the medium of a clockwork time release set for two-minute operation. Circuits are arranged so that time delay must follow the change of signal from proceed to the stop indication.

*Sectional Route Locking.* Sectional route locking provides for the electrical control of detector locks on switch levers throughout an entire interlocking route. When the interlocking signal is cleared for an approaching train, all switch and opposing signal levers are locked mechanically in the machine. The electrical route locking becomes effective when a train passes the signal governing movement through the interlocking.

*Detector Locking.* Detector locking is the electrical control to the normal and reverse locks of switch levers which acts to prevent movement of switches located within the limits of a track circuit in which a train is located or within a section of route locking in advance of the train.

*Track Circuits.* The operation of approach, route and detector locking in interlockings and the control of both interlocked and automatic signals is all based on the signal track circuit. Track circuit limits are defined by insulated joints placed in the track rails. At one end of the circuit current is fed to both rails of the track from a 300-volt-ampere transformer with variable secondary voltages. At the other end a relay is energized from rail connections. When a train enters the circuit, track current passes through the wheels of the rolling equipment short-circuiting the normal current path and deenergizing the relay. The deenergizing of the track relay opens the front and closes the back contacts over which signal circuits are controlled. All of the track relays used in electrified territory are of the centrifugal frequency type which are selective between the 25-cycle propulsion current and the 100-cycle signal frequency. These track circuits are divided into single and double rail types. The double-rail circuit is used in automatic signal territory and requires a double coil impedance bond at each end of the circuit, to provide a return for the propulsion current. Single-rail track circuits are used in interlockings where the control of route and detector locking requires that each signal block be divided into a number of short track sections.

In the single-rail track circuit one of the rails is bonded straight through for propulsion current, the other rail is equipped with insulated track joints to define track circuit limits.

The use of single rail circuits results in a saving in installation costs, as the only impedance bonds required are where the single-rail track circuits adjoin the double-rail type of the approach or receding track circuits to the interlocking. Double-rail track circuits vary in length,where drainage and ballast conditions are favorable, a maximum length of 5,000 ft is permitted. The length of single-rail track circuits is limited to 1,200 ft so as to provide for broken rail protection.

*Switch Operation.* Power-operated switches whether of the all-electric or electropneumatic type are controlled directly from rotary circuit controllers mechanically connected to levers of the interlocking machine. This control (usually 110-volt a-c) actuates a polarized controller at the switch for all-electric movements or an arrangement of *Z* armature electropneumatic valves on the air plants. Actual switch operation is thereby controlled locally at the switch. In the electric movement the switch operating circuit is energized through contacts on a polarized controller from the 100-volt mains. In the same manner air is controlled locally at the switch from the main air line for the pneumatic movements. In each type of switch movement, motion is conveyed to switch points by means of a slide bar carried on anti-friction rollers or guides to the switch operating rod through an open throat jaw or escapement crank.

The slide bar also provides a mechanical lock for switch points in both the normal and reverse positions. Locking dogs riveted to the slide bar are so arranged that they enter a narrow slot in switch lock rod, which is directly connected to the switch points. Coincident with the locking of the switch, the power is automatically disconnected from the operating mechanism and switch points held in position by the mechanical lock. A switch point tolerance of not more than 3/16 in. is permitted in the adjustment of this mechanical lock.

Having provided an operating control and a mechanical lock for switch movements, it is clear that a check should be made to insure that the switch has followed the movement of the control lever in the interlocking machine and that the switch is mechanically locked. This is accomplished by controlling the electromagnetic switch indication lock through a three-position switch repeating relay. This lock acts to prevent placing the switch lever in full normal or reverse position until the switch has completed full movement of points and is mechanically locked. The indication circuit is a polarized control of a three-position, two-element vane type relay, in which controller mounted on and actuated by movement of slide bar in the switch mechanism acts as a pole changer to the control element of the switch indication relay. This polarized control energizes the relay in a predetermined position when the switch is normal and to the opposite position when the switch is reversed. Circuits on the controller are so arranged that control wires to the switch repeating relay are shunted during the time that the switch is in transit. This same polarized switch repeating relay is used to control the clear position of signals routing through the plant.

Switch operation may be summarized as follows: First movement of slide bar unlocks the mechanical connection to the switch points and opens control of switch indication circuit, continued movement of slide bar actuates the switch points, the final movement of bar locks switch in the opposite position and closes indication circuit.

*Lightout Protection.* The lighting of signals is controlled over relay contacts with lighting circuit energized by a special 110/10-volt lighting transformer located in a relay housing adjacent to the signal. A special circuit was developed to check against a burnout of the lamp filament. The circuit arrangement provides a rectifier-controlled d-c relay in series with the lamp lighting and lamp filament circuit. Through this scheme of control it is possible to indicate the actual lighting or failure of a signal lamp by the medium of repeater lights in the tower.

Lightout circuits provide for the following features:

Automatic transfer of lighting circuit from an approach or clear indication to stop, in the event of a burnout when approach or clear is displayed; information is repeated to towerman who can then clear slow-speed signal for the route.

Checks that red lamp is lighted on normal route signal before proceed or approach indication can be displayed in restricted route signal. Under this circumstance the slow-speed signal may be cleared.

Checks that all red lamps are burning when signal lever is placed in normal or stop position, by controlling the approach locking circuits over lightout relays.

*Model Board.* Manipulation charts are provided in each interlocking tower indicating the proper sequence of switch and signal lever operation for the various routes. In addition to this chart, an illuminated model board is provided on which a complete track diagram indicates the location of switches, signals, track circuits within and the approach circuits to the interlocking. Track circuit limits on model board are defined by colored sections of track including a miniature light in each section which is illuminated when that particular track section is unoccupied. Model board lights also repeat the stop and clear signal indications of the interlocked signals and in addition, the indication displayed at distant signals approaching the interlocking.

With this arrangement the towerman can follow the movement of each train from the time it enters the approach section until the interlocking proper is cleared and it makes possible the control of two or more interlockings from a central point.

A summary of interlocking control in the sequence that it occurs follows:

1. The approach indicator and annunciator bell indicates the approach of a train.
2. Route is set by means of power-operated switches with repeater lights and electric locks indicating track circuit conditions and checking switch operation.
3. Signal is cleared, mechanically locking all switches and opposing signals in route, approach electric locking becomes effective, indication of interlocking home and the distant signal is repeated in the tower.
4. Train passes interlocked signal releasing approach locking, signal lever may now be returned to stop position, sectional route and detector locking becoming effective.
5. Release of route and detector locking in the rear of a passing train permitting a change in route for another move.

*Train Control—Loop System.* The first installation of train control was made in 1925 on the Atlantic City Railroad covering a territory of 55 miles between Camden and Atlantic City. The system installed is a continuous speed control with speeds of 85, 40 and 25 miles per hour imposed, together with a three-indication cab signal indicating high, medium or low speed. High speed or 85 miles per hour which is maximum permissive speed on this branch is imposed in clear blocks, medium speed of 40 miles per hour between a caution signal and braking point in approach of a stop signal and low or 25 miles per hour between this braking point and the stop signal and while passing through an occupied block.

In this system there is a two-element train-control relay located on the locomotive, the track element being energized through what is known as an axle circuit. The secondary of the track transformer is connected across the rails at the receding end of track circuit, current flows through one rail toward train in circuit across wheels and axle of locomotive to opposite rail, thereby completing the circuit. The flow of this current in the rails induces a second current in a receiver on the front end of the locomotive mounted a few inches over the rails, this current is then passed through special power amplifier tubes and then to one element of train control relay. The other element receives energy from a combination line and track circuit known as the loop circuit.

This loop circuit requires a special transformer connected through resistance coils to both rails of the track circuit, and the circuit is completed through a line wire running the entire length of the block which is connected to both rails of the track circuit at the opposite end. Current flowing in the loop circuit (through both rails in parallel and line return) is picked up by a second receiver mounted on the rear of the locomotive and through amplifiers energizes the local coils of the train control relay.

The three-position train control relay assumes a vertical position when either or both of its control elements are deenergized, and is energized in a predetermined position when both elements have a current flow with a certain phase relation, and energized in the opposite position when current in one of the elements is reversed. This change of phase relation is accomplished through the pole changing of the line or loop circuit as the polarity of track elements is always constant. The polarity of loop circuit is controlled through the position of wayside signal controlled two blocks in advance of the one occupied, thereby coordinating train control and cab signaling with the wayside signal indication. The electropneumatic brake equipment and cab signals on the locomotive are actuated by local circuits controlled by the train control relay above described. The current for operating this local equipment is supplied from a special generator which also serves to furnish power for the electric headlight of the locomotive.

*Train Control—Continuous Code Type.* The second installation of train control was made on the Bethlehem Branch in 1927, extending from Jenkintown to Bethlehem, a distance of 46 route miles.

The system installed is a continuous two-speed code type with four-indication cab signaling, a low speed of 20 miles per hour being imposed under certain track or block conditions. Unlike the loop system of train control previously described, where the train control relay was actuated from a combination of track and line circuits, the code system depends entirely on track or axle current. Code energy flows in one rail of track to the front wheels and axle of the locomotive returning to the transformer through the other rail. This flow of axle current induces a second current in receiver coils mounted on the locomotive ahead of the front wheels. The two receiver coils are electrically connected so that the voltages induced in them are additive when alternating current flows in opposite directions in the two rails. The circuit of receiver coils is tuned to resonance at 100-cycles and induced current passes through two stages of transformer coupled amplification to a master transformer and relay, which in turn actuates the several decoding relays tuned to a code frequency for the various cab signal indications and the pneumatic brake control.

Code is obtained from a small motor-operated coder through which the various code frequencies are superimposed on the track circuit coordinated with the position of wayside signal equipment for two blocks in advance of the one occupied.

Control codes are as follows:

| Frequency | Indication |
|---|---|
| 180 | Clear |
| 120 | Approach medium and imposed slow speed |
| 80 | Approach and imposed slow speed |
| 0 | Stop with imposed slow speed |

It is characteristic of both the loop and code system of continuous train control that any change in conditions occurring at any time in the clear block immediately causes a change to a more restrictive signal in the cab or locomotive and functions to initiate an automatic application of the brakes. Conversely, cab indication and control of automatic brake equipment is released immediately following any change in conditions ahead, which would make a higher speed permissible.

The arrangement of pneumatic brake control necessitates that the engineman operate an acknowledging lever when a change to a more restrictive indication occurs. The engineman then has a six-second interval to initiate a reduction to the imposed speed that is permitted with the particular cab indication being displayed. Unless the engineman immediately acts to acknowledge and reduce speed, train control equipment will function and stop the train. With this form of pneumatic control it is impossible for an engineman to observe a restrictive indication at wayside signal in advance of the train, forestall the application of brakes and proceed at an unauthorized speed.

## Discussion

For discussion of this paper see page 313.

# Centralized Traffic Control and Train Control
## of the Baltimore and Ohio Railroad

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and
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Non-member

***Synopsis.***—*This paper describes the facilities provided for centralized traffic control and gives detailed information with respect to two installations on the B. & O. Railroad. The operation of an intermittent inductive auto-manual train stop system on the B. & O. Railroad is also discussed.*

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### CENTRALIZED TRAFFIC CONTROL

*Purpose of System.* The purpose of a centralized traffic control system is to concentrate at one point under the direction of one operator the control of train movements over a long section of track, and to expedite the movement of traffic in that section. This is accomplished by bringing within view of the operator, indications as to the location of trains and the position of all switches and controlled signals, and also by bringing within his reach means whereby he is enabled to change, when safe to do so, the position of switches and signals affecting the movement of trains.

*Devices Employed.* A centralized traffic control system incorporates practically all of the devices and appliances ordinarily installed in a low-voltage interlocking system and a complete single-track automatic block system. Rails are bonded, insulated and otherwise equipped to provide complete track circuit protection. Hand-operated switches are equipped with switch circuit controllers which if opened more than one-fourth inch, prevent the display of a signal indication more favorable than "stop," or "stop and proceed." Dual control switch machines, *i. e.*, switches that may be operated either by motor under the control of operator or by hand at his direction, are used at the entrance and exits of passing sidings, junctions and ends of double track. The normally open hand-operated derails located on commercial sidings near the fouling of main track, are equipped with switch circuit controllers, through which the signals governing main track movements are wired. Relays perform the usual duties in the operation of the system, and in addition are wired to provide local protection in the field in lieu of route and detector locking. They are also extensively used in combination with the transmission system. Line conductors for the block signal, indication, and coding circuits are carried in aerial cables.

Color position light signals—standard under all methods of signaling on The Baltimore and Ohio Railroad—provide the indications which govern the movement of trains without the use of train orders. The signals consist of a cluster of lights, two red, two yellow and two green mounted either on a high mast in which case they are called high signals (Fig. 1), or on a lower support in which case they are called dwarf signals. Dwarf signals provide the same indications as high signals and are controlled in the same manner.

Red lights are displayed horizontally and when lighted indicate "stop." Yellow lights are displayed diagonally rising from left to right, and when lighted indicate "approach next signal prepared to stop." Green lights are displayed vertically and when lighted indicate that two or more blocks are clear.

These colored lights provide block protection for all routes, and are augmented by white markers to indicate which route is set. A white marker above the blocking lights indicates the route is set and the track alinement is such that a train may, if the block is clear, move at normal speed. A white marker below the blocking lights indicates the route is set and the alinement is such that a train may, if the block is clear, move at medium speed. The absence of a white marker above or below proceed blocking lights indicates that train movements must be made at slow speed.

Signals located along single track sections between meeting points or junctions are automatic, and require no manipulation by the operator. Those located for the

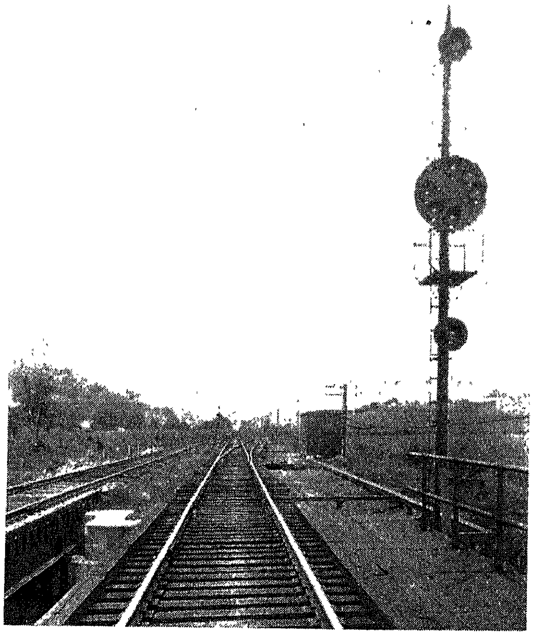

FIG. 1—HIGH SIGNAL GOVERNING OVER SWITCH AT A LAP SIDING

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*Baltimore & Ohio Railroad Co., Baltimore, Md.

*Presented at the Winter Convention of the A.I.E.E., New York, N. Y., January 23-27, 1933.*

protection of motor-operated switches are semi-automatic and have triple control, namely:

1. Automatic control, that is, by track circuit.
2. Switch control. Switches must be in proper position in order to provide an indication more favorable than "stop."
3. Manual control. Operator must, through the manipulation of levers, give his consent.

*Controlling Machine.* Operation of the above mentioned signals and switches is accomplished by means of a controlling machine. This consists of a control panel mounted vertically above and extending across the back and along the two sides of a flat top desk in such a way that all points on the panel are within easy view and reach of the operator or dispatcher. A diagram along the top of the panel shows the arrangement of the tracks, switches and signals controlled by the machine. Occupancy of a section of track by a train is indicated by the lighting of a miniature lamp in that section of the diagram. Rotating levers or knobs for the control of switches and signals are located under the track diagram, each lever or knob being situated directly beneath its corresponding switch or signal. In the immediate vicinity of each switch lever or knob is located one or more lights which indicates the position of the switch, also near each signal lever or knob is one or more lights which indicates whether a "stop" or a "proceed" signal is being displayed.

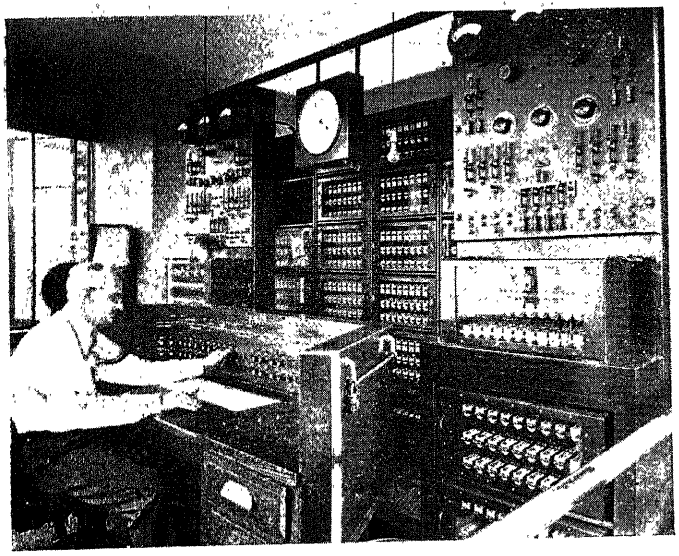

FIG. 2—CONTROL MACHINE AT WEST WASHINGTON, PA.

On the flat surface of the desk in front of the control panel is an automatic train graph which provides an automatic time chart record of all train movements through the controlled territory. Fig. 2 is from a photograph of the control panel and other associated equipment which actuate the indicating devices, signals and switches.

*Communication System.* The system is similar to supervisory control and printing telegraph systems in that the control of function is transmitted through the medium of code. This system was designed to meet the requirements of railroads for centralized control of a large number of field stations of relatively few functions each. The field stations are spaced, non-uniformly, generally at each end of a passing track, at the ends of double track, and at other points where switches and signals are controlled.

Station equipment is designed:

To operate switches in either their normal or reversed positions.

To control signals in either their "stop" or "proceed" positions.

Field stations are controlled one at a time, on successive cycles of operation. Office codes transmitted to field station are started manually by the operator. In the event that controls are initiated to several different field stations in rapid succession, the controlling pulses will go to one station at a time, in a predetermined order, fixed at the time of installation. The miniature lights on the control panel show for each controlled station:

1. Switches normal or reversed.
2. "Stop" or "proceed" signals displayed.
3. Whether a train occupies the short section of track which includes the switch.
4. Whether a train occupies the track approaching the switch.

Field codes transmitted to the control office are started automatically by the energization or deenergization of the control relays. Field stations send in their indications, one station at a time on successive cycles, and in the event that several stations initiate indications simultaneously, they will act to transmit their indications one station at a time in a predetermined order, fixed at the time of installation. Field code equipments are identical and interchangeable in each individual system. Each station is, however, responsive only to its own code.

## DESCRIPTIONS OF INSTALLATIONS

Two major sections of single track centralized traffic control on The Baltimore and Ohio Railroad—one extending from Gilkeson, Pa., to Wheeling, W. Va., a distance of forty-three miles, and the other from North Lima to Roachton, Ohio, a distance of fifty-six miles;—were placed in service during the year 1931. Prior to these installations trains were dispatched by means of time-table, train orders and a manual block system. These methods became inadequate properly to care for the number of trains being operated and there were consequently excessive delays resulting in overtime. The principal delays were occasioned by:

1. The necessity for stopping trains when entering or leaving a siding, and for stopping or slowing down to receive train orders.
2. The enforcement of manual block rules which do

not permit another train to enter a block occupied by a passenger train.

3. Inability of trains to make their meeting or passing points at the time calculated by the dispatcher, due to causes beyond his control.

These delays made it necessary to provide additional track capacity either through the medium of double tracking or through the installation of centralized traffic control. A comparison of the estimated cost of the two mediums resulted in the conclusion to install the C.T.C. system.

### Gilkeson, Pa., to Wheeling, W. Va.

A system known as the G-R-S Duplex Centralized Traffic Control is now in service between Gilkeson, Pa., and Wheeling, W. Va.

The control machine is situated in the second-story of a fire-proof tower located at West Washington, Pa. The installation includes the operation of switches, at eleven passing tracks and at the end of a double track, as well as the signals at these locations. A total of 23 power-operated switches, 70 controlled signals, and 38 automatic block signals is involved in the project.

As its name implies, this system provides for the simultaneous transmission of controls to, and the receipt of indications from, the same or different field stations. Two circuits extend from the control tower to the ends of the C.T.C. territory, one for outgoing control, the other for incoming indications. The system is normally at rest and is automatically set into operation whenever the operator uses the control machine, or by a change in field conditions requiring the transmission of a new indication. During the first portion of the cycle, when the system is set into operation, a particular combination of positive and negative impulses on successive steps, select the field station being called by the operator to receive new controls, or if a field station is in control of the transmission it will either open or leave closed the indication circuit on the sucesive steps to register its identity in the control office. Any one of 128 different stations may be thus selected or registered on the seven station selecting steps. After the selection or registration of a field station, the eighth step conditions the system for the next part of the cycle, comprising the last eight steps, which is used for transmitting controls or receiving indications.

The movement of a switch lever does not start a code if moved alone, but the code is initiated by the movement of a signal lever to the left or right or by operation of its associated starting button. To line up a route the dispatcher operates the proper switch levers and signal levers. This starts the operation of the relays comprising the code system. The first set of impulses select the proper field station and the following impulses cause the proper action of the signal apparatus at the selected field station.

### North Lima, Ohio to Roachton, Ohio

The installation between North Lima, Ohio and Roachton, Ohio is known as the U.S. & S. Co. Three Wire Circuit Code Scheme. The three line wires comprising two normally closed circuits with a common return, are of No. 12 gage in cable.

The control machine is situated in the second-story of a fire-proof tower at Deshler, Ohio, Fig. 3. The installation includes the operation of 34 motor-operated switches such as shown in Fig. 4, 88 controlled signals, and 34 automatic block signals. There is no interconnection between code circuits extending north and those extending south of the control office. Each circuit includes one relay in each field station and office, all in series. A circuit code is used, no time interval being employed except at the completion of a code.

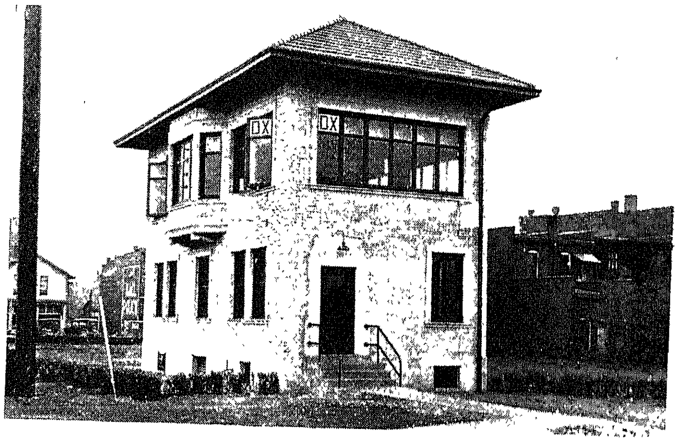

Fig. 3—Tower at Deshler, Ohio

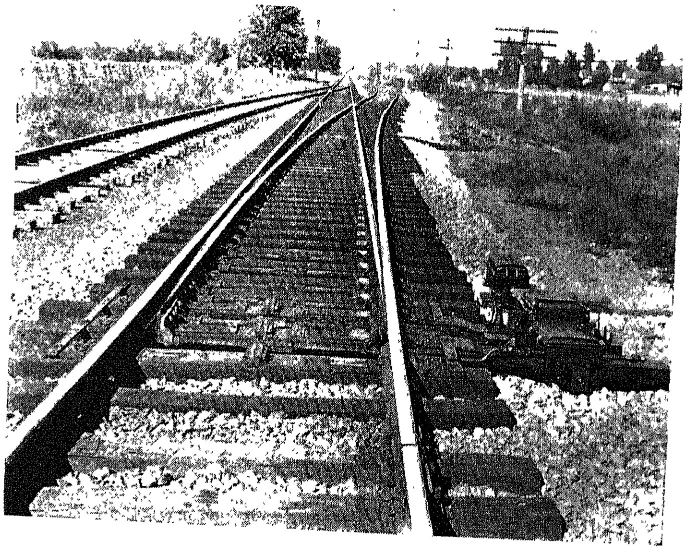

Fig. 4—Power-Operated Switch, Controlled from Deshler, Ohio

There are eight open circuit steps which may be generated at the office or at any station by counting chains of fifteen relays. Any of the eight open circuit steps may involve the opening of the first circuit only, the second circuit only, or both circuits, that is, three circuit conditions. The first step is primarily to differentiate between office and field-initiated codes and to lock out others, the office codes always starting with both circuits open and the field codes with either single line open. The first step locks out and prevents code sending to all units except the one desired. If the office and a station start simultaneously, the office takes precedence. If two or more stations start at the same time, the one nearest the control office is completed first. The locked out stations are held back and function in their proper turn.

Office codes are started manually while field codes are automatically started, by disagreement circuits, closed whenever any indicated function undergoes a change. Four steps are allocated to station selection, and eighty-one different selections are possible. Three steps are for operating and indicating functions. The code of eight steps requires approximately 1.5 seconds or 0.1 second for each counting relay, and it is interesting to note that about ninety-five total relay operations per code take place at each station. This short code period is necessary in large installations because there are times when a considerable number of codes must be transmitted in a brief space of time and delay is often not tolerable.

Due to these requirements of reliability and high speed, it was necessary to take care of variations in temperature, local battery voltages and relay adjustments, and to require positive registering of each step at all receiving stations before completing the step, the time duration of a code being that of the slowest code equipment. If a station fails to respond with reasonable promptness it is dropped out, permitting all others to function.

## SUMMARY

The systems operate as intended.

Train delays incident to the opening and closing of passing siding switches or stopping or slowing down for train orders have been largely eliminated.

Expenditures for operating labor, overtime and fuel have been reduced.

Track capacity is greater due to the closer spacing maintained between following trains, and safety of operation has been increased.

## INTERMITTENT INDUCTIVE AUTO-MANUAL TRAIN STOP SYSTEM

In 1922, the Interstate Commerce Commission issued an order to 49 Class 1 Railroads requiring each of these roads to make an installation of automatic train control on a full passenger locomotive division by January 1, 1925. In January, 1923, the Commission issued an extension to this order whereby 47 of the original 49 roads were required to install train control on a second division and 45 additional roads were required to install control on one division, thus involving a total of 94 roads and 141 passenger locomotive divisions.

As The Baltimore and Ohio Railroad was affected by the Commission's order to the extent of two divisions, it became necessary to investigate the principal systems offered at this time and select the one best adapted to its requirements. The territory first proposed and later approved by the Commission was from Baltimore, Md., to Washington, D. C. Although the distance between these two cities is only 34.6 miles, yet due to the very heavy passenger traffic, it was thought that this territory would offer a severe and thorough test in performance and capacity for any system.

It was essential that a system should be chosen which would not only meet the Commission's requirements, but one which would not reduce the capacity of the line. After much detail study recommendation was made that the General Railway Signal Company's "intermittent inductive auto-manual train stop system" be installed, not only between Baltimore and Washington but also between Baltimore, Md., and Philadelphia, Pa., a distance of 92.5 miles to meet the requirements in the second order of the Commission.

## DESCRIPTION OF THE SYSTEM

This train stop system is superimposed on the automatic block signal system.

The block signal system makes use of the track rails in combination with relays and insulated joints dividing the trackway into blocks. A potential is impressed across the rails at the leaving end of the block, the rails being bonded into a conductivity continuous circuit to the entering end. A translating device such as a relay responding to low potentials is located at the entering end, and controls the indications of a wayside signal installed at that point. When the track rails are continuous and the trackway is unoccupied, the relay at the entering end of the block will be energized, thus transmitting such indication to the wayside signal, permitting an oncoming train to run with unlimited speed in so far as occupancy of the particular track is concerned. By overlapping the control, the signal indicates the condition of two successive blocks. Thus if the two blocks ahead are clear the signal will show the indication "proceed with speed," while if only one block in advance is clear, the indication displayed is "prepare to stop at the next signal." This indication is usually termed the caution one. When the block immediately beyond a given wayside signal is occupied or its rails are broken or other hazardous conditions obtain therein, the signal at that location displays "stop and proceed, prepared to stop on vision." The observance of these restrictive wayside signal indications is enforced by means of the auto-manual train stop system.

The auto-manual train stop system consists of two distinct parts: the locomotive equipment, and the wayside equipment. The wayside equipment is a device known as an inductor, which is located approximately

70 feet in front of each block signal governing the entrance to a block in the direction from which the signal is approached and is placed just outside the right-hand rail. Although this inductor is electrically connected to its signal by two insulated wires, it normally carries no current. It consists of a U-shaped magnet with laminated cores, large pole pieces, and a coil which is connected to the front contacts of the signal control relay located at the base of the wayside block signal.

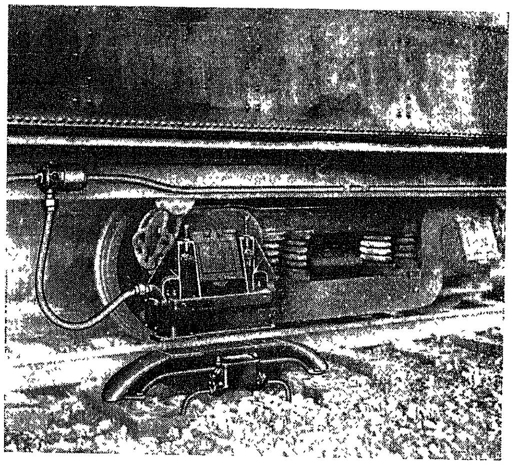

Fig. 5—Locomotive Receiver Over Wayside Inductor

The locomotive equipment consists of a receiver, a group of relays, electropneumatic valve, an actuator, a forestalling device, and a reset contactor. The receiver is mounted on the right side of the forward tender truck of the locomotive in such a location as to pass two inches above and directly over the inductor. There is no physical contact between the two. This device is an inverted U-shaped magnet with laminated cores and large pole pieces. It carries two coils, which are called the primary and secondary coils. Its general appearance is shown in Fig. 5.

The relay group is contained in a spring-mounted housing located on the deck of the tender tank. Its functions will be described later. The electropneumatic valve is located in the cab. It takes energy from the relay group and controls the brake-valve actuator. A brake-valve actuator is used to rotate the engineman's brake valve to the service position when an automatic application of the brakes is made. An acknowledging contactor located in the cab is used to forestall an automatic brake application by manually operating its handle. A reset contactor is located on the side of the tender and is operated from the ground after the train has been brought to a complete stop.

## Operation of the System

As the locomotive passes a wayside signal which is displaying a "caution" or a "stop" indication, its receiver passes over the inductor on open circuit, (see Fig. 6). A surge of magnetic flux builds up in the secondary coil of the receiver and produces a momentary negative current in the relay. This negative current is sufficient to allow the relay to open, and when once open, stays open until restored, due to its being a "stick" relay. The opening of the primary relay deprives the electropneumatic valve of energy which causes the valve to open and release the air from the larger piston of the actuator. The actuator, therefore, moves the brake valve to the service position which applies the brakes to the moving train.

The system is so arranged that the engineman can at all times operate his brake valve to the service or emergency position, but he cannot release the brakes manually during an automatic application. To restore the system to normal and release the brakes after they have been applied by the system, it is necessary for him to leave his seat and operate the reset contactor.

If the engineman is alert and fully capable of handling his train, he can forestall a brake application when passing a "caution" or "stop" signal indication by operating an acknowledging contactor located within easy reach of him in the cab. Under this condition a whistle sounds when the receiver passes over the inductor; when the whistle stops, it indicates that the acknowledging lever should be restored to normal position. He must, however, release the handle in 15 seconds. If he held it for a longer period, the brakes would be applied automatically, but could be released after restoring acknowledging contactor to normal position.

When the train passes a wayside block signal which is displaying a "clear" indication, the coil of its inductor is on closed circuit. As a result, the receiver may pass over an inductor in the clear condition without a reduction of the primary relay's current intensity to the drop-away point. Therefore, the electropneumatic valve will remain energized and no brake application will be effected.

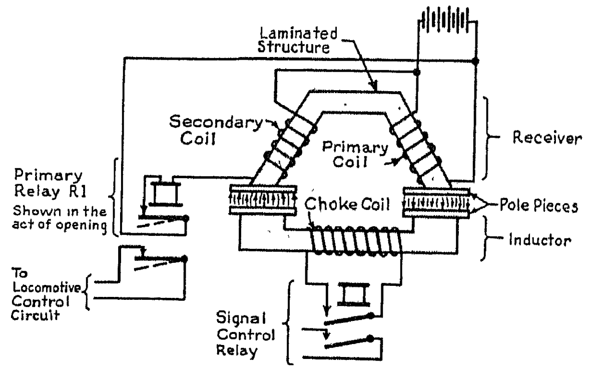

Fig. 6—Circuit Showing Principles of Control, Wayside to Locomotive

## Acknowledgments

Credit is given the General Railway Signal Company and the Union Switch & Signal Company for their cooperation in preparation of this paper.

# Discussion

## RAILROAD SIGNALING AND TRAIN CONTROL

(Amsden and Vandersluis)

## MODERN SIGNALING ON THE READING RAILROAD

(Reich and Wright)

## CENTRALIZED TRAFFIC CONTROL AND TRAIN CONTROL

(Davis and Dryden)

**W. A. Jackson:** No one seems to have thought to include anything of the history of the development of centralized traffic control, especially in view of the statement made that it was the most forward item of progress in railroad operation in 55 years.

About 20 years ago, soon after the development of the first selector for use on train dispatcher circuits, it occurred to one of the Telegraph Departments of the New York Central Lines that a selector could, in connection with the dispatcher's telephone circuit, be made to cause the operation of signals for various indications. I do not believe that any thought of operating track switches entered our minds at that time, but, of course, it must have been obvious later that if we could operate signals we could do most anything else. The first selector used was a Western Electric type which was called a telegraph selector. This was a good selector but the scheme had the serious fault that the same code of impulses that set up the signal, also cleared it, and the trouble was that the train dispatcher would occasionally forget that he had not cleared his signal and when he put it up for the following train the engineman would find the signal clear instead of set. It should be understood that there was no danger attached to this sort of operation as the only use for the signal operated by the dispatcher was to head a train in on a siding to let a following train pass, or to give him a passing record of the train by the location of the signal. The General Railway Signal Company became interested and developed a selector which was a splendid piece of apparatus and almost fool-proof. It had one fault, however, in that it depended on reversals of current and when the telephone line was patched in the case of trouble, or anything else happened that involved the changing of the wires, it upset the operation and the reversals of current were frequently, under such circumstances, of the opposite polarity of what they should be. Later, the Union Switch and Signal Company also became interested. However, it was not wholly a practicable arrangement for railroad operation until the development of the Western Electric so-called a-c selector, which is the same type as is used in remote control systems in the various lines of electrical power and communication work.

The writer thinks the centralized traffic control system was first placed in use between Berwick and Stanley Yard, near Toledo, along the Ohio Central Lines of the New York Central and that it was installed in 1927.

**R. M. Phinney:** Centralized traffic control, it is believed by many, is the first major development in the method of operation of trains since the introduction of the train order in 1851, over eighty years ago, and which it is now superseding on rapidly increasing mileage. There are now about 900 road miles of centralized traffic control in service, the first installation of which was made in 1927.

Among the many advantages of centralized traffic control there are two which, during this period of reduced traffic due to business conditions and the inroads being made by other means of transportation, can profitably be investigated as a source of immediate as well as continued economy:

1. The elimination of second and third track which was justified when built, but under present and in many cases future conditions, would not be required. There are many situations on multiple track lines where centralized traffic control can handle the traffic with one less track in service. The consequent saving in taxes and maintenance will amount in some cases to as much as $4,000 per main track mile per year.

In recent years there has been abandoned a large mileage of railway main line, for the most part branch lines, but a number of miles of second track has been included. The Irish railways lead the way by abandoning about 100 miles of second track.

2. The second item of economy that should be emphasized is the consolidation of interlocking plants. This merely needs to be mentioned as the economy is evident. This consolidation is continually going on but there are still many situations where efficiency of operation can greatly improve by consolidation.

**J. E. Saunders:** The papers demonstrate the similarity of the telegraph-telephone, and the railway signaling systems. The former covers the transmission of information by voice and telegraph; the latter principally by signs, color or position, through means of roadside and cab signals.

The primary purpose of railway signaling is safety. Its secondary purpose, which is that of providing a more economic transportation means, has come rapidly to the front during recent years. A pamphlet which will be published by the Signal Section, American Railway Association, in a few months will show the means of securing savings varying from 20 to 100 per cent per annum on the cost of making them effective, with typical specific examples where such savings have been demonstrated.

The paper presented by Messrs. Amsden and Vandersluis is of particular value to those who cover a wider field of electrical engineering in that it describes in a concise way the various ramifications of railway signaling and train control; that by Messrs. Reich and Wright, while applying specifically to the Reading Company, may be assumed as showing the general practise in more modern installations of signaling on electrified lines throughout the country. The paper by Messrs. Davis and Dryden covers in detail one of the more important and recent economic developments in railway signaling, centralized traffic control, as well as one of the systems of automatic train control.

It is interesting to know to what extent signal and interlocking practise on a railroad having direct current propulsion differs from one utilizing alternating current. These differences are given in the following and the points wherein the Lackawanna Railroad, New Jersey suburban electrification, deviates from the Reading, Philadelphia suburban electrification, which was put in at about the same time.

The Lackawanna power supply was 2,300 volts single-phase 60 cycles transmitted from substations which were so spaced as to make a higher voltage unnecessary. Since this frequency came from the primary source, frequency changers were unnecessary.

While the same type color light signal units were used, the Lackawanna system of simplified aspects permitted less units to be installed.

The track relays are of the inductive vane type and assume two positions, being energized when no train is on the track circuit and deenergized when there is a train. This compared with the a-c propulsion practise of using a centrifugal frequency relay which is running continuously during those periods when track circuits are unoccupied.

For line relays the Lackawanna utilized most of the d-c relays in service prior to electrification by inserting individual transformer rectifiers at the relays, thus accommodating a-c line circuits. Where three position relays were advantageous, for instance, for switch indications, a-c relays were employed.

The interlocking plants were either electro-mechanical or electro-pneumatic. Two former mechanical plants were combined in one electro-pneumatic, thus reducing operating expense. Electro-pneumatic switch valve magnets which formerly operated at 14 volts direct current were allowed to remain, a transformer rectifier being inserted in the control circuit of each thus permitting alternating current to be used.

There is no automatic train control effective in the electrified territory of the Lackawanna. However this railroad is operating trains on two-thirds of its main line between Hoboken and Buffalo under a continuous automatic train control system similar to that on the Reading. Trains operate under this protection for 3,600,000 miles per annum.

The signal and interlocking system on the Reading Railroad as described represents the highest grade construction and is in strict accordance with American Railway Association standards. It is evident to anyone who has inspected this that the materials used and construction methods followed are such as will insure long life and low maintenance expense as well as provide for the safe and expeditious handling of trains through the busy Philadelphia suburban district.

**G. H. Dryden:** The Baltimore and Ohio Railroad Company placed in service July 16, 1905 at Bellaire, Ohio, a system of switches and signals wherein one leverman-operator controls train movements over the Ohio River Bridge.

Three ends of double-track and one single-track junction are included in the installation. At the east end of the bridge viaduct a single track connects with the double-track line leading to Grafton, West Virginia and at the west end of the bridge viaduct the single-track line branches into a double-track line toward Newark, Ohio. Near the west shore of the Ohio River there is a branch line junction leading toward Cleveland. The total distance between the extreme ends of double track is 4,841 feet, and the farthest switches and signals from tower are 3,610 feet. Switches and signals are operated by 110-volt d-c motors, and information relating to the location of trains, the position of signals, etc., is obtained through the use of semaphore type tower indicators. No. 4 gauge wire was used in the control of the switch located at the east end of the viaduct. Trains are operated by signal indication. The combined system represents a simple form of centralized traffic control, and apparently the only reason for not having extended this system to include track sections of greater length, was due to the quantity of copper wire necessary.

The Berwick-Stanley installation on the New York Central Railroad is known as the unit wire control system, under which signals are transmitted over one wire for the control of: one switch in both normal and reverse positions; signals protecting the switch in each direction, and also for supplying information to the tower as to the passage of trains over the switch.

This system requires but one wire and common return from the central tower to each switch and is particularly adaptable at gauntlets and other points where the distances are not too great.

Under the code system it is possible to control any desired number of functions throughout a dispatcher's district, using two, three or a maximum of four line wires with the same degree of accuracy as is accomplished where an independent circuit is installed for the performance of but one duty.

Dual control switch machines mentioned in the paper are a recent achievement of manufacturers, without which numerous train delays would occur.

Controlled switches at ends of double track and passing sidings are in certain instances several miles from the headquarters of a maintainer, and should a failure occur due to obstruction in points, misadjustment, blown fuse or other cause, the dispatcher is unable to handle the switches by motor; this duty may be performed by trainmen at his direction. Also where train shifting is necessary, the duty of handling switches is assigned trainmen, thus enabling the dispatcher to devote his time to trains that are moving.

In conclusion, I desire to state—the C-T-C Code System of the Union Switch & Signal Company and the General Railway Signal Company, as well as the Unit Wire Control System, all of which are in successful operation on The Baltimore and Ohio Railroad, have passed the experimental stage, and that through their use track capacity is increased; the number of employees required in operation is lessened, and the running time of trains over a division is reduced.

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